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ELEMENTS
OF
GEOPHYSICS

AS APPLIED TO

EXPLORATIONS FOR MINERALS,
OIL AND GAS

BY
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Göttingen

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AUTHOR'S PREFACE

The systematic use of geophysical methods of exploration in mining and hydraulics, in the solution of water supply problems, and as an auxiliary to geologic research work is a child of the most recent times. The close contact of engineers and geologists with physicists and geophysicists, which practical work in this new field of investigation has brought about, has created such a number of scientific and technical problems that methods of applied geophysics are being introduced and developed in a rapidly increasing stream.

Numerous publications of various characters and with manifold objects, have already reported on many individual problems and limited parts of the field of applied geophysics. These reports, however, are scattered through the periodicals of the whole world.

Since the general basic divisions of a systematic grouping of the methods of applied geophysics have been somewhat established, it is desirable, and even necessary, to make a broad survey of this new field of investigation, reviewing the development of the various divisions, and summarizing the results which have been accomplished. At the same time an inspection of the present state of physical knowledge and theories may give an index to the future development of applied geophysics in meeting its problems.

It is not my intention to present a textbook of geophysics. Such a venture would extend far beyond the permissible compass of this book. Furthermore, it could not fulfill its purpose, since geophysical investigations require the collaboration of physicists and geologists with years of experience in these problems and technical difficulties, so different from the usual laboratory work of the physicist.

The fact that most of this geophysical work is undertaken by commercial organizations results—for easily understandable reasons—in the publication of papers which are incomplete. The most important points are often treated secondarily, or are suppressed entirely. Consequently, the selection of a report

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on any section of the field is very difficult. Frequently, the publications whose display of maps and diagrams makes them seem most comprehensive, in reality have an extremely poor scientific basis. In many of these publications there is no geologic foundation at all; this precludes any real test of the technical value which is claimed.

It must always be emphasized, that applied geophysics can never attain a completely independent position. It is a new and often very valuable auxiliary for the practical geologist, which increases the compass and range of his experience by introducing instrumental means of knowledge not immediately accessible to his senses and thus affords greater safety in his decisions. On the other hand, the comprehensive physical knowledge and experience, which are requisite for the planning and execution of geophysical investigations, forbid the geologist's making such measurements unassisted. The geologist and physicist are indispensible to one another in such work, except in rare cases. The geologist and the engineer should be thoroughly conversant with the general bases of applied geophysics in order to collaborate with the practical geophysicist. One of the most important tasks of this book, therefore, is to afford him this in a form adapted to his special field.

I hope also to give all those interested in mining and engineering a means of help in eliminating the chaff from the immense number of doubtful undertakings which spring up with the success of scientific work. Serious geophysical investigation requires trained workmen and much time, and this involves considerable expense. These costs, however, are vanishingly small in comparison with the capital required for the mining or engineering operations for which the investigation is preparatory. If the geophysical-geologic work fails, the capital is lost; the selection and execution of the right methods of investigation, therefore, justifies the expense. It will afford me especial satisfaction if my efforts in this direction, so important to national economics, can be of some benefit.

With this in view I have made my language as easily understandable as the difficulties of the subject allow. I have sometimes sacrificed complete scientific expression to general clearness. In order to afford a full survey of the present status of the field for the practical geophysicist, and those who wish

to do further work, however, I have added a bibliography of the most important literature at the end of the text.

The extent of the field to be covered and the shortness of time at disposal—the rapid development of methods of applied geophysics seems to me to require most urgently a systematic summary of their scientific background—have prevented my treating all sections with the same completeness. I shall be most grateful to professional colleagues, or any interested persons, therefore, for suggestions or corrections.

Finally, I wish to express my thanks to the publisher for his cooperation in all technical questions, and to a number of colleagues for their valuable counsel and assistance in the revision of individual sections.

RICHARD AMBRONN.

GÖTTINGEN
March, 1926

TRANSLATOR'S PREFACE

Within the past decade in this country the science of geophysics has come to the forefront as a method of prospecting. It is already being used to a slight extent in the search for several minerals, and the petroleum industry has been most enthusiastic in adopting the new science. Very little information on the subject has been published in English, however, and those who were interested have found great difficulty in obtaining foreign articles. This translation is offered in the hope that it may fill the need of the geologist, engineer, and business executive for a general idea of geophysical methods.

I wish to express my sincere thanks to Mr. E. DeGolyer for permission to undertake the translation; to Drs. Sidney Powers, D. C. Barton, Andrew Gilmour, F. M. Kannenstine, and especially Dr. J. C. Karcher, for their criticism of the translation.

MARGARET C. COBB.

NEW YORK, N.Y.
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ELEMENTS OF GEOPHYSICS

CHAPTER I

THE DEVELOPMENT AND PRESENT POSITION OF GEOPHYSICAL METHODS APPLIED TO PROSPECTING

Until recent years, the attempts of geologists and mining engineers to decipher the structure of the uppermost formations of the crust of the earth—either for scientific or for practical purposes—were confined almost exclusively to the systematic collection and analysis of those facts which may be obtained by immediate observation at accessible points on the surface of the earth, viz., at excavations, wells, or existing mines. Naturally, these observations were supported by those made in the petrographic, physical, and chemical laboratories. The miner commonly said: "Beyond the pick it is dark," meaning that only those facts which he could see with his own eyes were considered a safe basis for technical and economic plans.

As mining technique advances, deposits such as iron, coal, and oil can be worked profitably at greater and greater depths. On the other hand, the valuable mineral deposits discovered by surface evidence alone are being more and more exhausted and new ones are increasingly difficult to find in this manner. To an ever increasing extent, consequently, attention is being turned toward the exploitation of deposits not easily appraised above ground. But with increasing depth, it becomes more and more difficult to draw safe conclusions from geological facts ascertainable above ground regarding conditions underground. Prospecting and drilling costs likewise become greater. The risk in the use of old methods also increases disproportionately with increasing depth.

A further disadvantage of the direct method of investigation lies in the fact that observations can be made, at most, only at certain points over relatively large areas, unless Nature has provided especially favorable conditions, or unless unlimited

funds can be expended on the investigation. The character of the formations between these immediately accessible points is usually determined by interpolation or comparison with analogous conditions, a procedure which frequently leads to erroneous conclusions. At the present time, when the success of a mining enterprise depends largely on both the quantity and uniform quality of the mineral sought, a certain knowledge of the spatial configuration and character of the deposit is of the greatest importance.

For many decades, attempts have been made to develop methods for investigating geologic structure and the nature of the subsurface, which do not demand direct contact with the strata to be tested. These methods are based upon those properties of the desired mineral, or associated minerals, which produce effects which can be observed at some distance.

A great number of valuable mineral deposits—though in the light of present knowledge, by no means all—possess physical properties that may be detected at a distance. The problems that confront the geologist and mining engineer, therefore, should be attacked systematically with all the resources of modern physics and geophysics, in order to determine the range of the practical application of the known physical properties of matter connected with distance effects.

The investigation and measurement of distance effects arising from subsurface masses must be made at a sufficient number of accessible points with suitable areal distribution. This requires the most improved methods of geophysics and specially constructed apparatus.

The extent to which definite conclusions as to the structure of the subsurface can be drawn from the results of the areal measurement of distance effects will depend upon most careful tests of the specific physical properties of the different materials composing the earth's crust and upon the mathematical laws governing the distribution of field induced by them, *i.e.*, upon the characteristics of a field of force produced by them or of a current field influenced by them. This problem will be given especial consideration in the individual chapters which follow, since the *practical economic* value of geophysical methods of investigation depends primarily upon this test.

In fairly early times, certain characteristic properties of some minerals suggested to miners and prospectors the use of these

properties in the search for workable deposits. Magnetic iron was the first of these minerals to be considered. In earlier centuries, the northerly direction of the compass needle was ascribed to the effect of a so-called magnetic mountain which was supposed to be composed of magnetic iron ore. W. Gilbert, in 1600, was the first to assert that the earth as a whole was the magnet which influenced the magnetic needle. In Sweden, especially, about the middle of the nineteenth century, methods were developed which used magnetic measurements in the search for deposits of iron ore. The high electric conductivity, as well as electrochemical effects of many sulphide ores (pyrite, galena, etc.) in contrast with the surrounding rocks, was also recognized in England and Germany at the beginning of the nineteenth century and attempts were made to use this characteristic in the search for deposits of such ores.

These first attempts, however, did not lead to any *systematic* application of geophysical methods to prospecting, due largely to the fact that the observations were made, not by physicists who were fully acquainted with the theory of such measurements, but by mining engineers who were not sufficiently conversant with physics to find means of surmounting the difficulties that confronted them. Under the circumstances, occasional favorable results were obtained, but in many of the more complicated cases they must have been disappointing. Until recently, mining and geology on the one hand, and physics on the other, were too widely separated for deliberate cooperation; the sciences of physics and geophysics were developed sufficiently to encourage this only during the course of the last decade. The present high perfection and wide application of geophysical methods to prospecting quickly followed.

The study of the structure of the earth, originally for purely scientific purposes, fortunately, prepared the way for this geophysical development. On the physical, or geophysical-geodetic, side, this led to the perfection of gravity measurements, which at first were made solely to determine the true form of the earth's surface and its stability. The stimulus was thus given for systematic development of physical and geophysical methods based on the study of distant effects exerted by the various rocks which compose the crust of the earth. This led, naturally, to an investigation of their application to mining and other engineering problems.

Comprehensive treatment of this entire field of investigation in the light of modern physical and geophysical hypotheses has led to a systematic arrangement according to the principles given below, which were first proposed by Ambronn (28, 29).[1]

The methods of applied geophysics may be divided into two groups.

The first group comprises those processes which are based on physical properties of the geologic elements of the subsoil that produce an immediate distance effect. Here belong those processes concerned with the measurement of gravitational and magnetic fields and radioactivity. In this group also are included the effects of differences in electric potential due to chemically different substances or to those substances which are uniform in themselves, but which have local chemical differences. Analysis of the electric current excited by these electrochemical differences of potential in the soil has been used to detect the existence and spatial arrangement of otherwise unsuspected masses in the subsoil. To avoid repetition, the detailed treatment of practical cases belonging here will be appropriately arranged in two subdivisions under the general heading of earth investigations by means of electric currents.

Electrostatic forces and heat rays will be disregarded in this connection, since they play only a subordinate role. The older geologic and mineralogic methods of investigation, which depend upon the analysis of light rays visible to the eye, *i.e.*, upon visual observations, will naturally not be considered here.

The second group comprises processes dependent on the fact that the constituents of the subsoil through their physical peculiarities influence the development and distribution of currents of energy which are produced either naturally or artificially. Measurements of the variations from its normal spatial distribution can give much information on subsurface geology. To this group belong electric, electrodynamic, geoelectric and thermal methods of investigation.

Another method can be added to this second group: namely, measurement of the absorption of rays belonging to the first group by formations lying between the source of the rays and the place of observation might give clues to the characteristics of these intervening formations. An example of such a case cannot be given at present, however, as the soil formations absorb these rays too completely to exhibit effects of practical importance.

[1] Numbers in parenthesis refer to the bibliography at the end of the book.

Of practical importance, also, is a further difference between the methods belonging to these two groups. The field of gravity and the earth's magnetic field are entirely incapable of influence on the part of the observer and, accordingly, their structure must be measured as dependent upon the subsurface alone. In electrical measurements by means of artificially produced earth currents and in seismic investigations by means of artificially produced elastic waves, on the other hand, the observer may freely vary the form of energy used in diverse manner and thereby change the conditions of the investigation in many ways. (See Ambronn 33*c*.)

Geophysical methods of investigation can also be divided into two groups according to their practical application.

1. In many cases, physical properties of the desired mineral itself can be used for a fairly exact determination of the underground position and even of the individual characteristics of the deposit. (This is the direct method.)

2. Still more numerous, however, are those cases in which geophysical research methods afford only an indirect means of solution. Here, the object sought exhibits no physical property yielding a distance effect sufficiently characteristic to serve as a basis for measurement. Although the deposit is not in itself detectable, however, a careful examination of the problem very often reveals a regular genetic, tectonic, or other connection between the desired mineral and the structural elements in the subsoil, which lend themselves to geophysical methods because of characteristic physical properties that yield force effects at a distance.

As an example of the great multiplicity of possibilities for such indirect application of geophysical methods, the search for oil may be cited. Only in the rarest cases can oil be directly detected by its insulating properties, by means of electric currents.[1] Nevertheless, the search for oil accumulations, indirectly, is furthered by a number of the most diverse geophysical methods. The general geologic conditions in the region concerned determine the choice of the particular method for each case. With respect to those oil deposits that are encountered on the flanks of salt domes, one can determine the position and exact boundaries of

[1] Contrary assertions, recently advanced, have been sharply rejected, since they are not fully established from a physical standpoint. (See, for instance, Ambronn 33*b*.)

the salt domes, and the subsurface profile of its top and flanks, by means of seismic, gravity, magnetic, or electrical measurements. If the oil-bearing formation is simply connected with an anticline, comprising an alternation of beds of harder and softer formations within the folded series—as is almost always the case—seismic methods can accomplish signal service by permitting a most exact areal analysis of the system of folds. On the other hand, if formations with different magnetic properties are folded, magnetic measurements may yield valuable information. The distribution of concentrated salt water, which often stands in certain definite relations to the oil-bearing formations in oil regions, can be detected by means of electrical methods. From these random examples of the application of geophysics to the search for oil, it is clearly evident that the search for a substance which cannot itself be detected physically can yet be extraordinarily advanced in an indirect way by geophysical methods.

All physical and geophysical methods of investigation based upon distant effects have this advantage: that at every point of observation all parts of the subsoil, in proportion to their distance, are represented. The distribution of each physical effect in question is clearly determined by the subsurface distribution of the mineral whose physical property causes this effect. Every deposit with definite physical properties which are due to the desired mineral must make itself known by virtue of the special laws of its effect at a distance. In this way, the physical structure of the subsurface is obtained, uninterrupted and spatially complete, through investigations by applied geophysics.

One main condition for the successful application of geophysical methods—the disregard of which has done much injury to the cause of geophysics—cannot be overlooked: The relation of the spatial distribution of physical properties in the subsoil to the formation of fields of force, etc., on the surface of the earth is not easily reversible. The same distribution on the surface of the earth can correspond to various underground arrangements. The greatest care must, therefore, be taken to assure a correct geological interpretation of measurements which in themselves are entirely correct.

In this task of interpretation, it is preferable to consider the problem from more than one point of view. While the number of mathematically possible solutions for such a series of geophysical measurements may be unlimited, the range of explanations possible in Nature is notably limited, since the physical

constants of the earth's constituents which mainly come into consideration are qualitatively and quantitatively encompassed in rather narrow boundaries. Thus, the specific gravity of a rock can scarcely exceed 10, the electrical conductivity cannot be above a certain limit, etc., as can be seen from the tables of physical constants in the various chapters.

The very considerable fund of known geologic data further limits the number of possible interpretations of mathematical physical observations. It must again be emphasized that geophysical investigations which lay claim to scientific accuracy and integrity must include a preliminary geological survey in order to select the physical method or methods most suitable for each individual case. In the practical application of geophysical methods, the geologist has already gone far towards a qualitative solution; nevertheless, the geophysicist may still discover the quantitative conditions. A formation which is an especially good conductor in the subsoil at several hundred meters depth in North Hanover, for instance, can indicate only porous formations which are filled with highly concentrated brine. In the Harz, however, a mass, probably conducting just as well, must be supposed to consist of iron ores. An electrically non-conducting mass in North Hanover may describe a salt dome, dry limestone, or perhaps an oil-bearing formation. Only measurements of the density of the mass, its magnetic properties, or the velocity of sound in it can lead to an indubitable solution of the problem.

Thus an indispensable condition for a successful investigation is the selection of the proper method. Economic and financial considerations, as well as scientific and technical ones, must be taken into account. After choosing the most effective property or combination of properties for discovery of the mineral, attention must be paid to the location, size, and mode of occurrence, and, finally, all possible information for estimating the quality of the deposit.

In geophysics, as in geology, there is thus no one method which is useful and suitable for all purposes. In planning a geophysical survey for geologic structures or deposits, a complete knowledge of the whole field of geophysics is necessary in order to choose the method or methods most suitable for the particular area to be surveyed. The following chapters give a systematic discussion of the theory of the individual methods, the possibilities of practical application of the methods and the groups of problems that can be solved by them.

CHAPTER II

THE INFLUENCE OF THE SUBSURFACE FORMATIONS ON THE CHARACTER OF THE GRAVITATIONAL FIELD AT THE SURFACE OF THE EARTH

The gravitational force at any place, that is, the force which the earth exerts on a mass of 1 g., is the resultant in both magnitude and direction of the individual effects of all the elements of mass of the entire earth. Two point masses separated by a distance r and whose masses are m_1 and m_2, respectively, attract each other, according to Newton's law, with a force

$$k = \varkappa \cdot \frac{m_1 \cdot m_2}{r^2}. \tag{1}$$

If k is measured in dynes (1 dyne = 0.00101976 gram-weight), m_1 and m_2 in grams, and r in centimeters, then, according to the present most reliable determinations (904, p. 28; 774),

$$\varkappa = 6.67 \cdot 10^{-8} \text{ dynes.}$$

A critical compilation of all the determinations of the gravity constant made up to 1900 is given by Boys (233).

The gravitational constant is independent of the material of which the mass in question consists, as numerous and extremely careful investigations of Bessel (181), Baily (91), von Eötvös according to the comprehensive reports of Pekár (1217) and Roth (1304), have shown.

Eötvös, Pekár, and Fekete (403) have demonstrated, by means of the torsion balance, the gravitational constant's independence of the chemical and physical nature of the mass concerned for magnalium, snakewood, copper, water, copper sulphate (crystallized and in aqueous solution), asbestos, and talc, with an accuracy of the order of 10^{-9} of the value.

Solutions of silver sulphate and ferrous sulphate were examined before and after reaction with one another. The invariability of the gravitational constant appeared with the same precision. The gravitational effect of the sun's mass on the adjustment of the

beam of a torsion balance, on which a mass of magnalium was opposed to a mass of platinum, also proved independent of the material. Furthermore, the absorption of gravitational force was investigated. The absorption of the gravitational effect through a layer of lead 5 cm. in thickness proved smaller than $0.02 \cdot 10^{-9}$. Correspondingly, the absorption through the earth along its diameter would be smaller than $\frac{1}{800}$ of the total earth attraction. Majorana (1037) made similar investigations with corresponding results.

The influence of the radioactivity of a substance also fails to affect its behavior in the gravitational field.

Thus, the law of proportionality between heavy and inert masses has been confirmed with all the accuracy at present available and the gravitational constant's independence of the material of the masses on one another has been established.

The statement of Brush (263) that the gravitational constant for bismuth, a very strongly diamagnetic metal, deviated essentially (up to 28 per cent) from the normal value, has been refuted by Potter (1250), Wilson (1636), and Berroth (179). The influence of the pressure on the relations of a mass in the field of gravity was investigated by Brush (263*a*).

Shaw (1436) believed that he could establish a temperature effect on the gravitational constant, although Shaw and Davy (1437) could show that the attraction of two masses of lead, whose temperature varied between 0° and 250°, on two silver spheres hanging on a torsion balance was constant within this range of temperature. Poynting and Phillips (1251) also found only vanishingly small variations.

The gravitational effect on crystals (zircon, quartz, tourmaline, topaz, gypsum) was further established by Heyl (721), by weighing, as independent of the direction about the crystallographic axes up to 10^{-9} of the value. The constancy of the mass of crystals independent of the direction of the force of gravity with respect to the crystallographic axes was demonstrated up to $4 \cdot 10^{-8}$ of the value by Zeeman (1656) on two spheres of rock crystal of about 217 g. mass, by weighing. Changes in the chemical combination of several components, according to the extraordinarily careful investigations of Landolt (903), are also without influence on the effects of gravitation.

Since the force which acts on a mass found on the surface of the earth is composed of the sum of the individual forces emanat-

ing from all the volume elements of the earth, the attraction of the earth on each body is also proportional to its mass.

The Geoid.—A surface, such as the surface of the sea, is known as a *geoid*. The projection of this surface under the continents corresponds to the water level in a canal which would have free communication with the sea.

If the water level of the sea were raised or lowered (apart from the gravitational effects produced by the mass of water added or subtracted) further geoid surfaces would be obtained the outer of which would completely enclose the inner. The force of gravity everywhere is exactly perpendicular to this geoid surface. Central forces, such as the force of gravity, possess a potential, and a system of surfaces to which the force is everywhere perpendicular is designated as a system of equipotential surfaces. The conception of potential refers to the work which must be performed in order to transport a unit of mass from the equipotential surface in question, against the force of gravity, to infinity. This work is independent of the path along which the unit mass is moved. An equipotential surface thus forms the totality of all points from which a mass (1 g.) can be moved to infinity with the same expenditure of work U, which accordingly characterizes the equipotential of a geoid surface.

The force with which a unit mass is attracted by the earth is, on the one hand, equal to the acceleration of gravity g, but on the other, it is also equal to the change of the potential U perpendicular to the equipotential surface along the line dh

$$g = -\frac{dU}{dh}$$

The negative sign indicates that with a displacement of the mass upward, dh thus being positive, work must be performed against gravity. The closer the equipotential surfaces (also called level surfaces) lie together, the greater is the value that g assumes, and conversely. While the perpendicular to the geoid surface gives the direction of the force of gravity (the plumb direction), the magnitude of the acceleration of gravity is inversely proportional to the distance between two adjacent geoid surfaces.[1]

The Form of the Geoid.—The acceleration of gravity is composed of the gravitational effects of the mass of the earth and of

[1] Geoid surfaces are thus not surfaces of equal gravity, as Krahmann (867*a*, p. 30) asserts.

the centrifugal force arising from its axial rotation. Under the effect of these two forces, there results for the geoid as a first approximation an oblate spheroid, in which, according to Helmert (694, p. 96), the flattening is equal to 1:298.2 (613*d*, p. 67). The normal force of gravity decreases along this spheroid from the pole to the equator. According to Helmert (694), the normal force of gravity g_o at sea level, dependent upon the geographic latitude, is given by

$$g_o = 978.030(1 + 0.005{,}302 \sin^2 \varphi - 0.000{,}007 \sin^2 2\varphi) \cdot \text{cm /sec.}^2.$$

More recent, but only slightly different, formulæ are given by Helmert (696), Berroth (177*a*), Heiskanen (683), Gutenberg (611, pp. 48 and 154, 613*d*, p. 72 *et seq.*, Lambert (896*a*)).

Further, the acceleration of gravity with height above sea level decreases according to the following relation

$$g_h = \frac{g_o}{\left(1 + \frac{2h}{R}\right)}.$$

Tables for the value of the functions represented by these expressions are found in Landolt-Börnstein (904, Table 10a). (See also Helmert (687), (696).)

On the continents, the height h above sea level obtained by leveling, does not coincide with the height above the surface of the sea according to the geoid surface. This is due to displacement by the mass above sea level in the vicinity of the point of observation by an indefinite amount. Since, however, this displacement is in general very small, it can be disregarded in practice. It may be mentioned, for example, that according to Galle (517) it reaches a maximum value of about 4.5 m. in the Harz. Masses outside the Harz, however, also contribute to this. In the Alps, Prey (1256) found, some 10 km. south of the Brenner, a value of 12 to 13 m. In Asia and America, the difference may increase to a maximum of about 50 m., according to Messerschmidt (1094, p. 131).

The influence of the profile of the earth's surface and the geologic structure of earth's crust on the form of the geoid will be discussed separately later.

Methods and Instruments for Determining the Absolute Value of the Force of Gravity.—At present, the reversible pendulum first used by Kater (801) is probably used exclusively for the purpose of determining the absolute value of the force of

gravity with precision. If a pendulum swings about a knife-edge A (Fig. 1), a straight line parallel to and vertically below the knife edge A, at that distance which corresponds to the length of the mathematical pendulum of equal period of oscillation, is designated as the center of oscillation line of the pendulum. If this line is likewise made into a knife edge B and the pendulum is allowed, after rotation of 180°, to swing about this knife edge, instead of about A, the same period of oscillation is obtained in both cases. (See Berroth 180*a*, p. 443, et seq.)

In order to utilize this fact for the determination of the length of a seconds pendulum, the knife-edges A and B are fastened in the body of the pendulum at a distance apart, approximately known from previous determinations, which corresponds to the length of a seconds pendulum or any other desired period of oscillation, and then the two weights C and D are moved along the axis of the pendulum rod until the periods of oscillation about the two axes are as nearly equal as it is possible to adjust them. The deviations still remaining are then determined by calculation. The measurement of the distance between the two knife edges must be made with the greatest care; constancy of temperature, or the most careful determination and consideration of temperature changes, is necessary. On account of the buoyancy of the pendulum in the surrounding air, the mass of air set in motion by the pendulum, and the air friction, the barometric pressure must be taken into consideration just as must the moisture content of the air, as Defforges (342), and Furtwängler (493*a*) have severally shown. Especial precautions must be taken to determine and eliminate the influence of the vibration of the support on which the knife edge rests, on the results of the measurements. Much precautionary forethought must also be taken in regard to the form of the knife edge, according to Helmert (691), Hecker (659), le Rolland (1297), and others. A definite substitute for Kater's reversible pendulum is formed by the pendulum proposed by Finger (928) with one fixed knife edge but with movable masses.

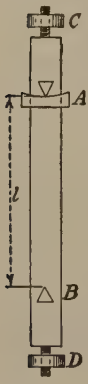

FIG. 1.

For the determination of the period of oscillation, the so-called method of coincidences is appropriately used. Since this also plays an important role in relative pendulum measurements, it will be described here somewhat more in detail. The method of coincidences serves to compare the periods of oscillation of two

pendulums. In making determinations by means of the reversible pendulum, its vibrations are compared with those of the pendulum of an astronomical clock, having nearly the same period and whose rate is controlled by means of astronomical time determinations of the greatest exactitude. A sharp mark on the pendulum, relative to its position opposite a scale, is observed through a telescope, which, in exactly the same phase at each oscillation of the pendulum of the astronomical comparison clock, gives free vision only for a moment. If the periods of the two pendulums are exactly alike, then at each glance in the telescope the mark on the reversible pendulum appears in precisely the same position on the scale. If the periods of the two pendulums are not exactly alike, then in the course of the oscillations the mark on the scale shifts. If after N oscillations of the clock pendulum the initial condition is again reached, then, in the meantime, the reversible pendulum has performed $N + 1$ or $N - 1$ oscillations accordingly as it is faster or slower than the clock pendulum. The period of oscillation of the reversible pendulum (or perhaps another pendulum to be compared) is then $N/(N + 1)$ or $N/(N - 1)$ times as great as the period of oscillation of the clock pendulum. An increase in the accuracy of the comparison is obtained by the observation of a great number of such coincidences. Photographic coincidence methods are described by Madsen (1026) and le Rolland (1297). In most recent times, wireless coincidental time transference, in connection with visual or photographic observation, plays an important role, especially in the carrying out of pendulum measurements in systems of points within limited areas, for investigating the structure of the uppermost formations of the earth.

If the rate of the comparison clock is known from the astronomical time determinations, then the exact period of vibration of the reversible pendulum can be calculated.

Such observations with a number of reversible pendulums were carried out in the years 1900 to 1904 in the pendulum hall of the Geodetic Institute, in Potsdam (52° 23′ north latitude and 13° 4′ east longitude, from Greenwich), at 87 m. above sea level, by Kühnen and Furtwängler (877), and gave as the length of the seconds pendulum

$$99.4239 \pm 0.0003 \text{ cm.}$$

From this it follows that the acceleration of gravity is

$$g = 981.274 \pm 0.003 \text{ cm./sec.}^2$$

Older determinations by other authors at other places, for instance, by Defforges (342), are less certain, because of incomplete consideration of systematic sources of error, but they agree within the limits of error with the value found in Potsdam.

Methods and Instruments for the Relative Determination of the Force of Gravity.—The inconvenience and difficulty of absolute measurements with the reversible pendulum make the instrument unsuitable for the determination of the force of gravity at the large number of stations which are requisite for the investigation of the distribution or disturbances of the force of gravity within large areas. Here, relative measurements suffice as they can be tied in with single stations at which absolute determinations have been carried out with every conceivable precaution. The pendulum apparatus of Defforges (342) is also used for relative gravity determinations in which measurements of the period of oscillation of the reversible pendulum contained in it are always carried out on both axes. This is to eliminate possible changes of the length of the pendulum and the dimensions of the pendulum body, which sometimes occur in the simple invariable pendulum (von Sterneck 626), since they could first be noted only by subsequent comparison at a standard base station.

The instrument which today, however, holds first place in practical consideration for relative measurements, is the so-called *invariable pendulum*, mostly after the pattern given it by the Austrian geodesist von Sterneck, and which, for example, Lorenzoni and Silva (979) describe in modern form. A number of other proposals for making such relative measurements possess now only historical value, as the apparatus of Perrot (1220), Pfaff's spring apparatus (geobarometer) (1228), the wind-vane regulator after Villarceau and Oppolzer (1564), Siemens' bathometer based on the principle of the spring balance (1444), the gas volumometer of Mascart (1048), Marec and Oppolzer (1203), Issel (790), which are reviewed in Günther's Handbuch (594, pp. 169–71) and by Oppolzer (1203). In more recent times, von den Borne (67) sought to improve the gas volumometer so that it would be applicable in the search for useful deposits of especially heavy or especially light materials. The earth's gravity was to be measured through its effect on a mass of quicksilver situated in a closed fluid manometer, which placed under pressure a quantity of confined gas whose temperature was so

regulated for the time being that the gas volume remained constant. The gravity was then obtained from the temperature of the gas space requisite for the compensation. Briggs (245) proposed to use this method for gravity measurements at sea Madsen (1025), Pfaff (1231), and Barus (104), also for investigations on land.

An *invariable pendulum apparatus* must be as stable as possible. Von Sterneck's pendulum, which, among others, is described and illustrated by von Sterneck (1483), in Günther's "*Handbuch der Geophysik*" (594, p. 189 *et seq.*), in Arrhenius' "*Lehrbuch der Kosmischen Physik*," (59 p. 243 *et seq.*), by Berroth (180*a*, p. 446 *et seq.*), Ansel (613, p. 504 *et seq.*), and in the most recent model by Heiland (674) (Lorenzoni and Silva also give very beautiful illustrations 979), consists of a pendulum weight in the form of two truncated cones with the greater basal surfaces united. These are fastened on a massive cylindrical rod perpendicular to their common base. At the upper end of the pendulum rod is the agate knife edge by means of which the pendulum is supported on an agate base. As long as the pendulum is not in use, it is raised on the support; the knife-edges are in use only during the time of measurement. The swing of the pendulum should not be more than a few minutes of arc. In practice, three or four such pendulums, with planes of vibration placed about 120° or 90° from one another, are fastened to a bronze support cast in one piece, so that instrumental errors can be determined or eliminated, especially the covibration of the stand and the subsoil, and so that a correlation of the results gained with the different pendulums, on which among others, Schumann (1408), Berroth (180), and Haid (626) have reported. The apparatus is enclosed in a case to guard against temperature changes as much as possible. The temperature is most carefully determined by means of an accurate thermometer suitably placed. The pendulum is in a vacuum. A contrivance for this is described by Haasemann (619, see also 979). Recently, according to Müller (1146), Meinesz (1068), and Lenox-Conyngham (941), such relative pendulum observations have been carried out with satisfactory accuracy on submarines.

The gravity pendulum, usually constructed as a half-second pendulum, is either compared with an astronomically regulated pendulum clock placed in the vicinity of the place of measurement, or several pendulum stations are simultaneously con-

nected by telegraph with a pendulum clock placed in a centrally located astronomical observatory. There can also be erected at the places of observation simpler pendulum clocks electrically synchronized by a centrally located master clock. The electric time transference can also be made, as in longitudinal determinations, by wireless, or, according to Hammer (637), by earth currents. Heyl (721*a*) and Quayle (1258*c*) suggest the possibility of the comparison of the oscillations of a gravity pendulum with the vibrations of a tuning fork, in order to shorten the duration of observations.

Where, as on the sea, *e.g.*, Duffield (364), Swick (1504*b*), the erection of such a rigid pendulum apparatus is difficult, a method which was proposed by Mohn (1122) and improved and tested by Hecker (662, 1257, 1643*a*), on long journeys, has proved accurate. This method depends upon the comparison of air-pressure measurements by the mercury barometer on the one hand and of a boiling-point thermometer on the other (1258, p. 50 *et seq.*). When gravity changes under otherwise constant exterior circumstances, for instance if it becomes greater, then the air pressure read on the mercury barometer becomes greater, in the same amount as the mercury column itself becomes heavier. The same mercury column thus maintains equilibrium with different air pressures. The boiling temperature of pure water, on the other hand, is dependent only upon air pressure, thus, it varies with gravity. A comparison of the air-pressure values obtained simultaneously by the two methods allows the value of gravity to be found. The differences are, however, very small, and demand an accuracy of some 0.001° C. relative to the boiling temperature of water and of some 0.01 mm. relative to the mercury barometer. The exact barometric level, difficult to obtain on a rolling ship, is acquired by averages from permanent photographic registrations. The motion of the moving ship also necessitates corrections, since this influences the magnitude of that part of the gravity acceleration which arises from the centrifugal force of the axial rotation of the earth. The application of this method to the land is discussed by Kowatscheff (866).

Methods and Instruments for the Determination of the Gradients of the Force of Gravity and the Curvature of the Geoid Surface.—If U designates the potential of gravity, and if xyz signify the coordinates in a rectangular coordinate system, then the equation of the level surfaces is

$$U(xyz) = C,$$

where C denotes a constant which becomes smaller from potential surface to potential surface outward.

Then for all points P outside the earth, Laplace's equation applies:

$$\frac{d^2U}{dx^2} + \frac{d^2U}{dy^2} + \frac{d^2U}{dz^2} = 2\omega^2, \tag{1}$$

where ω indicates the angular velocity of the earth's rotation around its axis. For points P within the earth, however, Poisson's equation applies:

$$\frac{d^2U}{dx^2} + \frac{d^2U}{dy^2} + \frac{d^2U}{dz^2} = -4\pi\varkappa^2\sigma + 2\omega^2. \tag{2}$$

Here there appears a term which contains the density σ of the soil near P, as well as the gravitational constant; hence this term is likewise known. The observations for the determination of the form of the geoid aim to establish the function U itself or its spatial variations.

Now

$$\frac{dU}{dz} = g, \tag{3}$$

if z has the direction of the perpendicular to the geoid surface. The differential quotients taken in the tangents to the geoid are

$$\frac{dU}{dy} = 0 \text{ and } \frac{dU}{dx} = 0. \tag{4}$$

Further, d^2U/dz^2 signifies the change of the force of gravity along the line perpendicular to the geoid surface, and the second derivatives

$$\frac{d^2U}{dxdz} = \frac{d^2U}{dzdx} = \frac{dg}{dx} \text{ and } \frac{d^2U}{dydz} = \frac{d^2U}{dzdy} = \frac{dg}{dy} \tag{5}$$

denote the changes of the force of gravity along the x- or y-axis in a direction tangential to the level surface.

The total horizontal gradient of g is

$$\frac{dg}{ds} = \sqrt{\left(\frac{d^2U}{dxdz}\right)^2 + \left(\frac{d^2U}{dydz}\right)^2} = \text{Gradient } g, \tag{6}$$

and its direction relative to the positive x-direction (in general taken along the meridian through the place of observation toward the north) has the azimuth α, given by

$$\text{tang } \alpha = \frac{\dfrac{d^2U}{dydz}}{\dfrac{d^2U}{dxdz}}. \tag{7}$$

Because of the irregular form of the surface of the earth, the level surfaces of gravity are usually not parallel to one another; thus the lines of the force of gravity, or plumb lines, which cut all level surfaces of gravity perpendicularly, are curved. Their radius of curvature at the point xyz is given by

$$r = \frac{g}{\sqrt{\left(\frac{d^2U}{dxdz}\right)^2 + \left(\frac{d^2U}{dydz}\right)^2}}. \tag{8}$$

If (vertical) plane sections are taken through the level surfaces of gravity in the direction of gravity at the point of observation xyz, then the traces of the level surfaces are curves whose curvature can be determined at the point xyz by the radius of the circle which fits them best. Of all these osculating circles, the planes of the smallest and the largest are perpendicular to each other and determine by the size of their radii ρ_1 and ρ_2, the curvature of the level surface at the point, xyz.

Furthermore,

$$\frac{1}{\rho_1} + \frac{1}{\rho_2} = -\frac{1}{g}\left(\frac{d^2U}{dx^2} + \frac{d^2U}{dy^2}\right), \tag{9}$$

and, according to equation (1) for point xyz lying outside the earth,

$$\frac{1}{\rho_1} + \frac{1}{\rho_2} = \frac{1}{g}\left(\frac{d^2U}{dz^2} - 2\omega^2\right) = \frac{1}{g}\left(\frac{dg}{dz} - 2\omega^2\right). \tag{10}$$

Further, there holds for the angle λ, which is inclosed by the cutting plane containing the larger principal radius of curvature ρ_2 and the xz plane, the relation

$$\text{tang } 2\lambda = -2\frac{\frac{d^2U}{dxdy}}{\left(\frac{d^2U}{dy^2} - \frac{d^2U}{dx^2}\right)} \tag{11}$$

Since

$$\frac{1}{\rho_1} - \frac{1}{\rho_2} = -\frac{1}{g}\left(\frac{d^2U}{dy^2} - \frac{d^2U}{dx^2}\right)\frac{1}{\cos 2\lambda}, \tag{12}$$

then from equations (10) and (11), if one knows

$$\frac{d^2U}{dx^2}, \frac{d^2U}{dy^2} \text{ and } \frac{d^2U}{dxdy}$$

separately, or at least the combined values

$$\left(\frac{d^2U}{dx^2} + \frac{d^2U}{dy^2}\right) \text{ or } \frac{d^2U}{dz^2} = \frac{dg}{dz}, \frac{d^2U}{dx^2} - \frac{d^2U}{dy^2} \text{ and } \frac{d^2U}{dxdy},$$

he can calculate the magnitudes ρ_1 and ρ_2 individually and thence determine the form of the geoid surface at the point xyz.

Finally, von Eötvös (399, p. 370 *et seq.*) introduces another magnitude.

$$R = g\left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right), \tag{13}$$

which is also given by the relations

$$\frac{d^2U}{dy^2} - \frac{d^2U}{dx^2} = -R\cos 2\lambda \text{ and } \frac{d^2U}{dxdy} = \frac{1}{2}R\sin 2\lambda. \tag{14}$$

λ and R are often especially well adapted for a graphic representation.

Further discussion will treat of the methods of determining the first or second differential coefficients of the potential function, in order to be able to calculate from them the individual characteristic magnitudes $dg/dz, dg/ds$, α, ρ_1, ρ_2, λ, and R, quoted above, for the form of the geoid surface and its distance from the adjacent surface, at the point of observation.

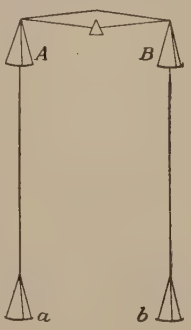

FIG. 2.

The determination of dg/dz was carried out by von Jolly (774) when, using a delicate balance, he measured the decrease with change in elevation of the weight of a mass.

In Fig. 2, this method is set forth graphically. From the balance pans, A and B of an extremely sensitive balance two other balance pans, a and b, are suspended, at a distance of h cm., by very fine wires. The two masses to be compared are placed either on pans A and b or on B and a, and the difference in weight due to this arrangement is determined.

Von Jolly found, using masses of 1 kg., a difference in weight of 1.662 mg. for $h = 5.3$ m., and for masses of 5 kg. a difference in weight of 33.06 mg. with $h = 21$ m. which agrees with the theoretical value to within 9 and 4 per cent, respectively. Messerschmidt (1094, p. 141) has compiled the results of a number of such measurements of dg/dz:

TABLE I

$dg/dz = 0.000,003,14$ theoretically, with elevation in free air above the sea
2,96 theoretically, with elevation above land at sea level
2,85 } Jolly in Munich (774)
3,01 }
2,78 Thiesen in Breteuil (1526)
2,79 Richarz and Krigar-Menzel in Spandau (1293, 1294)
2,95 Scheel and Diesselhorst in Charlottenburg (1354)
3,15 Helmert (Formula of 1901; 694, pp. 97 *et seq.*)

The influence of the accidental mass distribution in the immediate neighborhood of the place of measurement is included in these values. This partially explains the difference.

A 1-kg. mass becomes about 0.3 mg. lighter with each meter of elevation. Hence the balance is fifty times more sensitive to gravity changes with height than the invariable pendulum. A proposition of Berroth (178) for measuring dg/dz with a vertically swinging torsion balance has not yet been carried out experimentally. Attempts to make use of Jolly's method for determining dg/dz with portable instruments in certain problems of applied geophysics do not appear so hopeless with the modern advances in balance construction.

The determination of the remaining two derivations of the potential function U, treated in the previous section, is carried out with still greater accuracy with the help of the torsion balance used for this purpose by R. von Eötvös and since perfected. The publications of von Eötvös (396, 397, 399–402), Pekár (1218, 1219), Schweydar (1421, 1422, 1424), Gavat (521) Haarstick (618*a*), Ansel (613*d*, pp. 517, *et seq.*), Hecker (665, 666), Eggert (380), Heiland (672, 675), Schumann (1047), Shaw and Jones (1434), Tams (1506), Gornick (574, 575), Wünsch (1651*a*), Wagner (1573), Koenigsberger (839*a*), Venturi (1562), Nikoforov (1167), Inglada (770), Batemann (105), Berroth (180*a*, p. 465, *et seq.*), and others treat the theory and practice of von Eötvös' balance partly in highly mathematical, partly in easily understandable form. Heiland (677) gives a synopsis of the historical development of the torsion balance. In order not to make examples too voluminous, reference is made to these comprehensive special publications for all details and especially for the derivation and basis of the formulae applied.

There are two types of torsion balance: the first type can only determine the curvature magnitudes of the gravity level surface

at the station; the second type gives, in addition, the horizontal gradient of the force of gravity in both magnitude and direction.

Figure 3 indicates schematically the torsion balance of the first type. At the ends of a thin aluminum tube B there are fastened two equal masses, m_1 and m_2. A short rod which carries a small mirror is attached to the center of the beam perpendicular to its length. The system is suspended by a very fine platinum-iridium wire F. Threlfall and Pollock (1537), as well as Boys (233a), used a fine quartz filament instead. The single-crystal filament of tungsten, already proposed by Ambronn, in 1922, because of its favorable elastic properties, should prove effective according to Angenheister (51a).

If τ is the torsion constant of the suspending wire, ϑ the angle through which the balance beam turns under the influence of the force of gravity acting on m_1 and m_2 and the opposing rotational force of the suspension, K the moment of inertia of the balance beam about its axis of rotation, and α the angle which the axis of the beam makes with the x-axis of the coordinate system, then for the position of equilibrium:

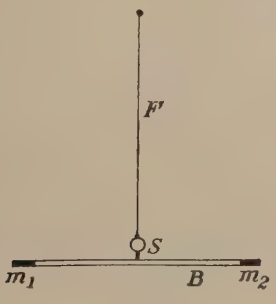

Fig. 3.

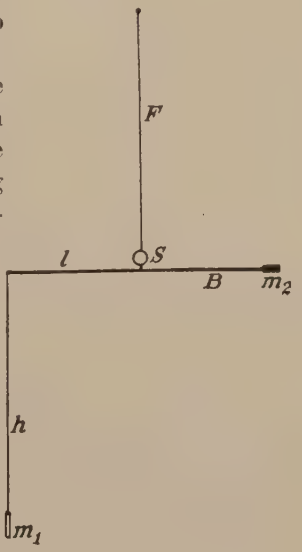

Fig. 4.

$$\vartheta = \frac{1}{2}\frac{K}{\tau}\left(\frac{d^2U}{dy^2} - \frac{d^2U}{dx^2}\right)\sin 2\alpha + \frac{K}{\tau}\frac{d^2U}{dxdy}\cos 2\alpha. \qquad (1)$$

Figure 4 shows the principle of the torsion balance of the second kind. In this the mass m_1 is not attached to the balance beam itself, but is suspended by means of a thin filament of length h, from one end of the beam at a distance l from the axis of rota-

tion, while the mass m_2, as in the torsion balance of the first variety, is fastened directly to the other end of the beam.

In the case of equilibrium between the rotation ϑ of the filament F and the torsion moment arising due to the inhomogeneity of the force of gravity at the place of erection of the apparatus, we have

$$\vartheta = \frac{1}{2}\frac{K}{\tau}\left(\frac{d^2U}{dy^2} - \frac{d^2U}{dx^2}\right)\sin 2\alpha + \frac{K}{\tau}\frac{d^2U}{dxdy}\cos 2\alpha - \\ - \frac{mhl}{\tau}\frac{d^2U}{dxdz}\sin\alpha + \frac{mhl}{\tau}\frac{d^2U}{dydz}\cos\alpha. \quad (2)$$

The magnitudes m, l, h, can be determined by direct measurement. K and τ are obtained by observation; τ may be obtained for both kinds of torsion balance when a lead ball of about 10-kg. weight, accurately made, is allowed to act on one of the masses of the torsion balance from a measured distance, and the rotation of the suspending wire effected thereby is measured; the gravitational constant, however, is supposed to be known. For increasing the accuracy of the measurement, the large ball is brought near the suspended weight of the torsion balance, on each side alternately.

If d is the change from the zero position on the photographic plate which intercepts the light ray reflected by a mirror at a distance Δ from a fixed source of light, $\varkappa$ the gravitational constant, M and m the masses of the deflecting lead ball and the suspended weight of the torsion balance, L the length of m, δ the mean distance of the lead ball M from the axis of the weight (usually cylindrical in form) on the torsion balance, and l the lever arm of the balance, then

$$\tau = \frac{4\Delta\varkappa}{d}\frac{Mm}{\delta^2}\frac{l}{\sqrt{1+\frac{L^2}{4\delta^2}}}. \quad (3)$$

K is determined from the value of K/τ, which is obtained from observation of the oscillations of the balance. If the balance beam is deflected from its position of rest and its period of free oscillation T is determined once in a position T and again in a position T_2 after rotation through 180° in order to eliminate the possible asymmetry of the field of gravity at the place of observation, then

$$\frac{K}{\tau} = \frac{1}{2\pi^2}(T_1^2 + T_2^2) \quad (4)$$

Equation (1) still contains two, and equation (2) four unknowns. Moreover, the zero position of the suspension wire, when it is without torsion, is also unknown. This position with respect to the xz-plane relative to which the angle α is measured is therefore to be determined or eliminated by observation, in accordance with equations (1) or (2). Thus, a full set of observations with the balance of the first variety comprises three measurements of the torsion of the wire preferably made by turning the balance through successive angles of 120°. A complete set of observations with the balance of the second type, however, comprises five measurements at angular distances of 72°. A still further increase in the number of positions is preferable, however, in order to increase the accuracy of the results and to be able to determine the accuracy of the values obtained by the method of least squares.

The speed of the work with the torsion balance of the second type will be considerably increased, according to a proposal of von Eötvös, if two balances are placed in the same box in positions different in azimuth by 180° so that their movement will be registered simultaneously on the same plate. The balance is then placed successively only in the azimuths 0°, 120°, 240°. With balances of the first kind the use of two balance beams placed at 30° from each other has been proposed for the same purpose. A further increase of the number of balance beams would scarcely prove beneficial in practice.

An idea of the actual space distribution of the forces effective on the two types of torsion balances is given in Fig. 5 (after Heiland (674)). Here N_1, N_2 indicate the two level surfaces corresponding to the two ends of the balance beam B, and N_3, the level surface cutting the center of gravity of the lower weight in the torsion balance of the second type. The forces P and Q_1 or Q_2, acting on the masses, are perpendicular to the level surfaces in question. Since P does not act parallel to Q_1 or Q_2, there results by vectoral subtraction (for both kinds of balances) the horizontal components d_1 or d_2, which, with their components perpendicular to the balance beam, lead to the torsional moment calculated above.

A most important point is to arrange the most careful protection of the movable part of the suspension F, the beam B, and the masses m_1 and m_2, against changes of temperature. For this reason the suspended system fastened to the torsion head T is

encased in a triple-walled case M of copper or aluminum tubing, as is apparent from Fig. 6, after Heiland (674, p. 419). The second balance beam, rotated 180°, lies behind the plane of the figure. The torsion of the suspended system is registered by means of the ray Ls passing from the lamp L to the fixed mirror W, thence at right angles to the movable mirror S of the suspended system, then back to W and thence to the photographic

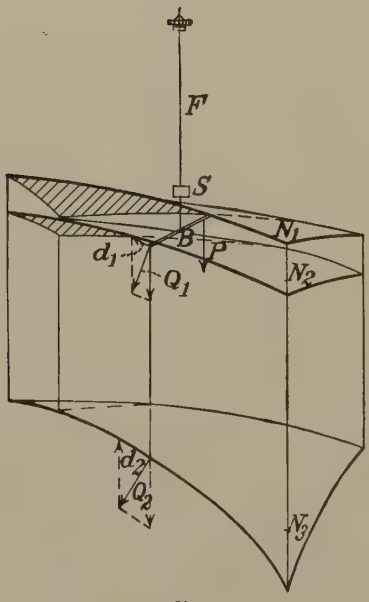

Fig. 5.

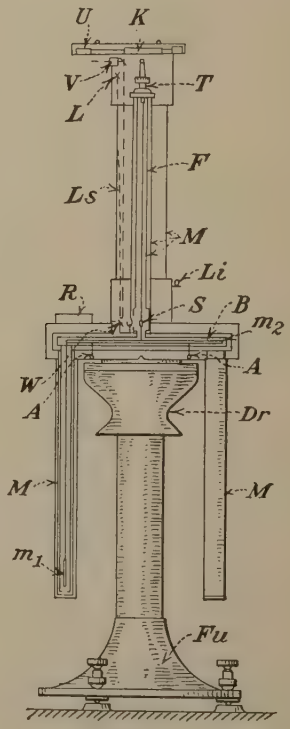

Fig. 6.

plate K which is moved slowly forward by the clockwork U. The advantages and disadvantages of this photographic registration, in contrast with visual reading of a balance, have been discussed fully by Pekár (1219) and Schweydar (1422). The photographic registration gives more convenient and certain results; however, the insertable glass plate V permits the deflection of the light rays Ls for visual reading in order to control the balance adjustment at any time (1601). All asymmetry in the

construction of the balance is avoided by arrangement of the registration apparatus on the top of the balance and by the circular construction of the base *Fu*. An arrester *A* protects the beam in transportation. The clockwork for the rotation of the whole balance through a sector in azimuth is provided in the base at *Dr*. A level *Li* and compass *R* serve for the adjustment of the balance case. When used in the field, the balance is packed in wadding, feathers, or similar material and placed in a double-walled tent. Although von Eötvös could work only at night, and even with such extremely careful protection of the balance against the rays of the sun, he still found disturbances in the zero point of the torsion wire, due to currents of air in the interior of the balance and elastic after-effects (*e.g.*, Koenigsberger 839*c*), yet today, according to Heiland (675), balances are made which work faultlessly even under the tropical sun in the daytime. In order to increase the speed of measurement, damping arrangements have been provided (65) and care has been taken that all movements of the balance shall be as gentle as possible (62).

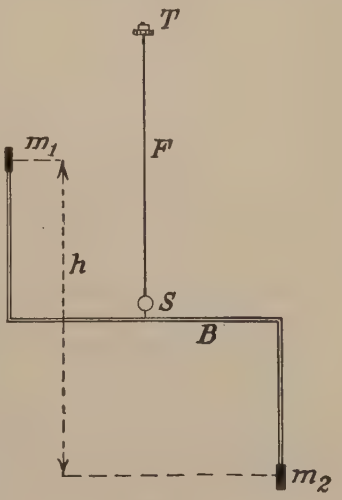

FIG. 7.

A notable advance is indicated by the introduction by the Askania-werke (66) of the Z-beam, after Schweydar (1425*a*), in which one of the masses is placed as far above the beam *B* as the other is below it. This is shown in Fig. 7. The height of the balance frame is substantially diminished. A later similar proposal of Haalck (616*b*) may be of less practical expedience.

The torsion balance with its accessories unfortunately has considerable weight; therefore, transportation into the field and from one station to another in the field is often very difficult. The balance beam is some 40 cm. long, the suspending wire *F* some 60 to 70 cm. and the height *h* at which, in the balance of the second type, the lower mass hangs beneath the balance beam, also amounts to some 60 to 70 cm. The introduction of the *Z*-beam lessens the former construction height about *h*/2. The

diameter of the torsion wire F is usually about $40/\mu$ (*i.e.*, 0.040 mm.), which corresponds to a τ of some 0.5. In order to facilitate transportation and to lessen the dimensions of the instrument, so that, for instance, it might be used easily in underground mining work, von Eötvös (401) instituted attempts with smaller suspended systems. In this case, thinner suspending (torsion) wires could also be used. Von Eötvös (401) again gave up the attempt at the construction of smaller torsion balances. Recently, Hecker has undertaken anew to reduce the size of the torsion balance in this direction. Holst (737) published results with such a balance in practical operation. Heiland (675) has made a comparison of the accuracy of measurement of torsion balances of different origin and construction. Measurements by means of a balance of von Eötvös (399 p. 353), a balance of the Askaniawerke after Schweydar (1422), and and a small balance after Hecker were made by Holst (737) and compared with one another. The advances in construction of this instrument are recognized from the tables given by Heiland, but the defects of too small form also are seen. Although the continuously rotating torsion balance after Kilchling (806*a*) or the torsion balances with shorter oscillation periods after Nikiforow and others, indicate advances in practice, they must be tested first by investigation under different working conditions.

Finally, some other possibilities of studying the geometric properties of the geoid surface, which are only of slight practical importance, may be mentioned here very briefly for the sake of completeness.

Deviation of the Plumb Line.—The plumb line at any place on the earth is always vertical to the level surface of gravity. Astronomical latitude and longitude determinations give the difference in direction of the plumb line at different places on the surface of the earth (Prey 1258 p. 21 *et seq.*).

On the other hand, two points at which the direction of the plumb line has been determined astronomically can also be connected with each other by a geodetic triangulation, in the calculation of which, however, the mean form of the geoid must be assumed as known. This form has been deduced from very extended triangulations in connection with astronomical observations and, as set forth on page 11, has been represented for example by Helmert's formula of 1900, since the local disturbances, which are always small, are compensated by means of the

large number of observations chosen for the purpose and thus brought almost to the vanishing point.

If the astronomical coordinates of a great number of points in a given region are determined by astronomical observations, if the region is next covered by a geodetic triangulation, and if the differences in the astronomical latitudes and longitudes are computed in contrast with the latitude and longitude differences of the points of observation, relative to a reference point, obtained by geodetic transference, we thus obtain for each place of observation the difference between the astronomically and geodetically determined plumb line. The latter is still dependent upon the form of the standard geoid chosen as the basis of computation and upon the choice of the reference point at which the deviation of the plumb line is assumed to be zero. For this reason, the deviations of the plumb line are not usually referred to an arbitrary normal or reference point in the consideration of large regions. From the large amount of material obtained from measurements already carried out from this point of view, there is now a system of plumb-line deviations so compensated that, in the main, the deviations in the various directions cancel (see Schumann (1409*b*). In this system the deviation of the plumb line for individual standard points in the various countries has been computed, and, in turn, all other points of observation in a given country have been connected with these principal points. The deviations of the plumb line then remaining are due to the heterogeneity in the structure of the earth's crust and their discussion can, therefore, be applied in drawing conclusions as to its structure.

Instead of giving the amounts of plumb-line deviation in the north-south and east-west direction, individually, the total resultant plumb-line deviation and the azimuth in which it lies may be used.

From the system of plumb-line deviations, there is obtained the angle which the true geoid surface at the point of observation forms with the standard geoid surface chosen as the basis of geodetic calculations. With a sufficiently close net of observation points, there can, therefore, be constructed progressively in such a manner the true geoid surface, beginning from a point in the region and proceeding in all directions in accordance with the angle observed there, as, for instance, was done by Galle (517) for the region of the Harz.

In the definition of the plumb-line deviation, the astronomic plumb-line directions and those obtained by geodetic transference are inseparably connected with one another. There is thus a complete misunderstanding in wishing to devise (for example, Quiring (1267*a*)) methods of determining plumb-line deviation by measurements at one observation place alone.

A possibility, at present only theoretical, of determining the change in plumb-line deviation along the surface of the earth, consists in suspending two equally long, equally high, plumb lines at some known distance from one another and in measuring the distance b of the lower end of the suspended threads from one another. The distance b will differ from the distance between the points of suspension because of the difference of plumb-line deviations at the two points of suspension in contrast with the normal value. Under the assumption that the plumb lines are arranged 1 m. distant from each other and are 2 m. long, the difference $a - b$ on the normal geoid would amount to some 0.0003 mm. The greatest difference in plumb-line deviation in the Harz, which, according to Galle (517), amounted to about 11″ with 15.5 km. distance between the stations Brocken and Hohegeiss, would change this difference only about 0.000,007 mm. This magnitude lying in the region of X-ray wave lengths is here immeasurably small, since in contrast to it, the changes with time of the materials of which such an apparatus is constructed become overwhelmingly large on account of variations in temperature, elastic after-effect phenomena, etc.

Levels.—The form of the true surface of the earth is established by means of levels. A line of levels results in establishing, with reference to a point A, the direction perpendicular to the plumb-line direction, thus parallel to the geoid surface. If an area which exactly fits the geoid surface is considered, then in proceeding by very small steps from point to point along the tangent to the geoid one would remain always on the geoid surface. This is especially true if, as happens in practice, in constantly sighting exactly along the horizontal from one point of the line of levels to the previous and to the following point, with the leveling points always the same distance from each other, only their difference in height is established.

If the region in which the measurements are carried out does not coincide completely with the geoid surface, however, as will generally be the case, then by forward and backward sights

with the telescope of the leveling instrument set horizontally along the tangent to the geoid surface at the point of observation (for instance, point 27), one must determine the difference in height Δh between the preceding (26) and the following point (28) of the line of levels. Then the leveling instrument is set up at the next point (29), situated, for instance, somewhat higher and the succeeding point (30) is connected with the point (28). If, however, in the region to be measured, the successive geoid surfaces at any point of observation are not parallel to one another, then, as can be seen at once, the difference in height which is measured between two points is dependent upon the manner in which the leveling has been carried out. The differences which can actually appear are too small to be usable for geophysical prospecting work. In running levels between the North Sea and the Adriatic Sea, where the great mountain chain of the Alps must be crossed, the total error from this cause was only a few decimeters. If, however, along the line of levels, one also knows the gravity disturbance or the plumb-line deviations at a sufficient number of points, then one can remove such conditional errors by calculation according to the method given in detail by Messerschmidt (1094, pp. 147–50), von Sterneck (1482), Prey (1258, p. 70, *et seq.*), Berroth (180*a*, p. 483, *et seq.*), and others.

If one sights exactly along the horizontal from a point on the surface of the earth (as along the tangent to the geoid containing the observation point), then the longer the sight, the further one deviates (along the line of the tangent to the geoid) from the geoid surface. If r is the earth's radius (about 6,370 km.) and h, the height of the line of sight at the distance a from the point of observation above the geoid surface (here considered as a sphere), then with sufficient approximation $h = a^2/2r$.

Thus, at the distance a, the line of sight lies about h mm. above the normal geoid surface, and

$a =$	0.05	0.10	0.25	0.50	1.00	3.00	10.00 km.
$h =$	0.2	0.8	4.9	20	78	700	7,840 mm.

If one now levels from one point to another, for instance, lying 10 km. distant, along a section of the normal geoid (radius of curvature = 6,370 km.), always sighting forward in 50-m. lengths, then one reaches the end in 200 lengths and has departed about $200 \cdot 0.2$ mm. = 40 mm. in height from the normal geoid

of the starting point. If one repeats the leveling with single stretches 100 m. in length, then one rises $100 \cdot 0.8 = 80$ mm. above the geoid of the starting point, or 40 mm. above the end point of the first leveling with 50-m. sections. With intervals of 500 m., the elevation would amount to $20 \cdot 20 = 400$ mm. and for a single sight of 10 km. even to 7.84 m.

For the solution of practical questions relative to subsurface geologic structure, the differences measured on the normal geoid naturally do not come into consideration, but only those changes caused by the distorted form of the geoid. If we again take as an example the above case (p. 28) of the differences in the plumb-line deviation of 11″ in the 15.5-km. distance between Brocken and Hohegeiss in the Harz, then we obtain in 10 km. a difference of plumb-line deviation of about 7″. The difference of plumb line direction on the normal geoid in 10 km. distance amounts to about 324″, thus some forty-six times as much as the disturbance. The difference in results of the two levelings with 50- or 10,000-m. divisional lengths on an undisturbed geoid and on one disturbed, as in the example, would thus differ from one another about one forty-sixth *i.e.*, about $7.80/46 = 17$ cm. The difference is, in itself, not so very slight, but it is questionable whether in measuring continually in the same direction, such an accuracy on the requisite sights can be obtained, because of the terrestrial refraction; while, in precise leveling, using forward and back sights and short divisional stretches, several hundred times greater accuracy can actually be attained. The writer is not aware of a practical test of the above method having been made; an attempt in a favorable region and with favorable weather conditions might perhaps be worth while.

Mention need only be made of the possibility of using the influence of the attraction of the sun and moon, as well as the effect of meteorological conditions, on the plumb-line direction, for example, in the shifting of low-pressure areas (Darwin (329)) and the vibrations of a horizontal pendulum, for determining the subsurface structure in the immediate neighborhood of a station. The basis for this, among other things, has been treated by Schweydar (1417, 1418, 1420), and Hecker (668). With the difficulties attendant upon a sufficiently stable erection of such an instrument and the duration of the series of measurements made with it, such investigations can scarcely come into consideration for the purpose of geophysical methods of prospecting.

But, from all points of view, it is to be noted that these elastic deformations, due to solar and lunar attraction, can act as the final impulse for the release of elastic tensions in tectonic structures of the crust of the earth. Earthquakes and possibly permanent changes of level in the region are the result. The value of earthquake phenomena for purposes of geophysical investigation will be taken up extensively in a later section.

Slow Changes of Level.—The idea that the formation of the relief on the earth's surface in previous earth history was brought about by the same forces as those still working today on the morphological structure of the earth's crust warrants an investigation of slowly occurring changes of height and their connection with tectonics. While Lyell (1010) based his observations on the changes of height of natural and artificial landmarks on the coast of Sweden, today the differences in the elevations of well-marked fixed points, found by repeated precision leveling extending over long periods of time, are used in such investigations.

Rapid changes in differences of elevation within a limited area appear frequently in connection with earthquakes and volcanic eruptions. Lallemand (894) and Lemoine (938) reported after the earthquake of June 11, 1909, in Provence, vertical displacements of several centimeters which reached their greatest magnitude along a great fault traversing the region.

Changes of level in and around Lake Constance during the earthquake of November 16, 1911, were established by Lauterborn (922) and Rütschi (1329). The careful, precise levelings and plumb line measurements of Costanzi (319) around and on the Strait of Messina in the region of the graben fault, there striking north and south, show the sinking of the earth described by Sieberg (1443, p. 76). Hammer (631) also reports on these researches; from his report the connection of the depression and the earthquake phenomena with the tectonic structure of the subsoil is clearly revealed. A noteworthy distance effect of earthquake vibrations on a region of tectonically deep-seated disturbance is indicated by the disturbance of the flow of the Teplitz hot spring by the great Lisbon earthquake of 1755, treated by Suess (1497). Oldham (1195) and Middlemiss (1103) have reported on notable changes of elevation as a result of earthquakes in India. Very large changes in elevation were noted repeatedly in the Japanese earthquake regions by Koto (862) and Davisson (333). Tarr and Martin (1519) described the great

changes on the Alaskan coast caused by the earthquake of 1899, and furnished many very interesting illustrations. Large horizontal displacements in the California earthquake of 1906 are connected by Rothpletz (1308) with the basic tectonic lines of this region.

As examples of change in level resulting from volcanic occurrences, there may be mentioned the reports of Hammer (630), Omori (1201, 1202), and Fenner (448), on measurements in Japan. On horizontal displacements resulting from volcanic activity, compare, for example, the measurements of Fennema (447) in Northern Sumatra and Malacca. It is doubtful whether the slow changes of level in the Gulf of Naples, thoroughly studied by Günther (592), are connected with the volcanic activity of Vesuvius.

Mention should also be made of the practical importance in geologic mapping of the local narrowly limited changes of level due to the formation of drains and sink holes through the solution of salts, gypsum layers, and similar easily soluble rocks.

For the solution of questions of the tectonic structure of a region, the slow elevations and depressions of more or less extensive areas of the earth as established by repeated precise levels are specially important and are of great interest in their relations to the problems of isostasy—relative to which see the detailed descriptions of Born (205, p. 86 *et seq.*). Descriptions of a general character in this direction are given by Hahn (623), Geikie (526), McGee (1019*a*), Krantz (868), Galitzin (504), Bicher (183), Fisher (453), Tams (1258, p. 319 *et seq.*); reference may also be made to the works of Soess (1462) and Nolte (1185). The last named, as well as Joly (783) and Tams (1507), support especially the contraction hypothesis and the calculation according to the forces working towards isostatic equilibrium. Wegener (1592), on the other hand, treats of the possibility of horizontal wandering of land masses. Special investigations on the connection of the observed changes in level within a single region, with its general tectonic structure and its geologic development have been made: for instance, by Schmidt (1398) and Wilser (1632) for France, where the movements show the possible after-effects of the north European loading of the glacial period; by Blaupot ten Cate (192) for The Netherlands, where other geophysical properties were also utilized; and by Horn (741) for Holland. In Germany, extensive work has been done: by

Schmidt (1397), Kranz (869), and Regelmann (1280) in the Alpine foreland, with its changes in level produced perhaps by the gravity disturbances due to the Alps, and by Wolff (1644) in the coastal regions, which are in movement from the after-effects of the loading in the glacial period. Very quick changes of level in a limited area have been established by Schumann (1405) on Telegraphenberg at Potsdam, and he believed that he was able to recognize in them relations to the changes in atmospheric pressure. In Denmark, Forchhammer (469), in Sweden, Ramsay (1271), and Nilson (1168), among others, have noticed changes in elevation within the most recent time. De Geer (343) considers the European North Sea as a field of depression; Witting (1640, p. 274) gives a map of slow elevations in the Baltic, which likewise still shows the after-effects of the unloading of this region since the Ice Age and thus may be referred to as a type of the isostatic adjustment process.

Visible displacements, which have been made accessible underground through mining operations, have been repeatedly noticed and quantitatively measured, as by Baumgärtel (134) in the Hartz, and by Haussmann (645) in the Aaschen Coal Basin. Of practical, and, in cases of accident, of judicial, importance (*cf.* Krusch 874) are the changes in level and slope which are caused by fracturing due to mining operations or to ground-water withdrawal in mining and deep construction operations. Recently Goldreich (567), Oberste-Brink (1190*a*), Klusche (815*a*), and Niemczyck (1164) have discussed the point of view which comes into consideration here. Niemczyck treats in especial detail the example of the Beuthen Basin, where depressions, due to purely tectonic conditions and changes of level through mining operations are found in the same locality.

Application of Gravity Measurements to Investigation of Mass Distribution in the Interior of the Earth.—The methods which have been described for the determination of the absolute or relative value of the force of gravity itself, or for establishing the curvature relations and the position of the level surfaces of gravity, yield these magnitudes only for the single discrete observation point itself. There follows, then, the further task of determining the true form of a single level surface and the distribution of gravity on it. The level surface coinciding with sea level, whose form is already given for more than two-thirds of the earth by the surface of the sea, can be selected for this

purpose. Then from measurements on higher-lying level surfaces (on the continents or on islands) one must deduce the position of the level surface coinciding with the surface of the sea and compute the distribution of the magnitude of the force of gravity upon it.

In the data for every high- or low-level surface, there enter the contingencies of the surface form of the region around the place of observation, the effect of the elevation of the point itself, and the distribution of density within the rock masses lying between sea level and the place of observation. For details of the methods used for the elimination of these accidental influences, and for the determination of the position and form of the sea-level surface below the place of observation, reference must be made to the literature cited. It has been shown that the mass distribution in the earth's crust, in spite of the differences in density of its separate layers, and in spite of considerable differences in elevation, is already so far statically compensated that the deviation of the sea-level surface from Helmert's formula of 1900, given above, or from another such formula for calculating the form of the level surfaces, is very small.

The form of the surface of the earth is deduced from trigonometric measurements, from the comparison of these with astronomical longitude, latitude, and azimuth determinations; and for the rigid part of the earth's crust, also from leveling. Leveling also gives the heights of surface points above sea level, by which the special influence of gravity through mass distribution, as briefly indicated above, can be obtained by calculation. Assuming that the earth possesses an approximately homogeneous density distribution arranged in almost concentric layers, the level surfaces thus being approximately parallel to each other and the small local perturbations mutually compensating, then the collection of all gravity measurements on the surface of the earth gives a method of determining its true form. All these methods considered together lead to the conclusion that an ellipsoid of revolution (spheroid) comes so near to the true form of the earth that the differences between the true sea level and the normal level deduced from the formula, due to heterogeneous density and obtained from gravity measurements, etc., scarcely exceed 12 to 15 m. in Europe and 50 m. in Asia.

With a structure of the earth's body, made up of homogeneous concentric shells, the true level surfaces would coincide with the

ellipsoid of revolution. But the masses of the continents and islands rising above the level of the sea, and the mass deficit in the oceans, which in comparison with a mean density of the earth's upper crust of about 2.7 g. per cubic centimeter, amounts to only 1.03 g. per cubic centimeter, disturb these ideal conditions, according to Newton's law of attraction. Historical geology teaches us that the profile of the surface of the earth has undergone great changes in the course of time. More or less extensive elevations and depressions of parts of the surface of the earth have interchanged land and sea. With elevations and depressions occurring during erosion and deposition, naturally, the temperature in the interior of the earth also changes. Thus, on the lower surfaces of the earth's sinking crustal layers, fusion of magmatic masses may occur, and solidification on rising; volume changes of these masses with the change in their state of aggregation may lead to displacements in the crust of the earth, as Sandberg (1339), for instance, explains. Also, within the solid state, allotropic modifications may change into one another, to which de Lapparent (906) has referred. High mountains are worn down by water, wind, and the rays of the sun, and the deep sea is filled by deposition of rubbish, sand, and dust. Great glaciations have covered extensive portions of the surface with ice masses hundreds of meters thick, the influence of which on the form of the geoid has been investigated by von Drygalski (360), Faye (446), Hergesell (710), de Lapparent (905, 907). The pressure of those glaciations has weighed on the surface of the rocks until climatic changes of cosmic or telluric origin has again caused the load to disappear. Through lateral thrusts, whose origins are not clear, beds of great size have been shoved over one another or highly folded. All these processes have continually changed the mass distribution on the surface of the earth. To what extent flowage or displacements of masses of different density also occur at greater depths in the earth's interior is still wholly unrevealed. Ampferer (35, 36), Andrée (39), Kossmat (861) (see also Tams (1286, p. 262)) believed such processes might be assumed. At 2 km. depth, according to Schmidt, in the Simplon tunnel (1396), no marked plasticity is present in the gneiss and chalk existing there. The phenomena of vulcanism can also be ascribed to such hypotheses; still, at the present time people are generally inclined to look for their origin in the higher formations of the crust of the earth (*cf.* also Sandberg (1338)).

To what extent the body of the earth may yield to pressure changes which are produced by the processes collectively mentioned above (a question with which, for example, Spencer (1466) has been concerned) will depend upon the rigidity of the material constituting the earth at different depths. It still does not appear possible on the basis of laboratory investigations to picture the behavior of the material which constitutes the crust of the earth at greater depths, although numerous investigations by Adams (8), Bridgman (244*a*), Graber (577), Kleinhaus (811), Milch (1105), Adams and Williamson (9), Joly (781), and others (see also Schneiderhöhn (1400*a*)) have made advances in this direction. On the temperatures predominating there, opinions also vary when it is recognized that at least a very considerable portion of the heat radiated by the earth into empty space, over and above that received from the sun, arises from radioactive charges in the upper formations of the earth. A very clear summary of the latest investigations relative to this question is given by Rösch (1299). Born (205) also expresses himself on these problems.

One is, therefore, thrown back on geophysical investigations of the rigidity of the individual formations. The determination of the deforming effects of the attraction of the sun and moon which (corresponding to the ebb and flow phenomena in the sea) are produced in the solid body of the earth, were made by means of the horizontal pendulum by Schweydar (1417, 1418, 1420, 1420*a*), Orlov (1203*a*), and Hecker (668*a*), by means of the water level by Michelson and Gale (1102), and from latitude fluctuations according to Wanach (1577), Schweydar (1418, 1419), Larmor (909), Hough (744), and Herglotz (711). These show that the earth opposes this deforming force of proportionately short period with a rigidity somewhat of the magnitude of steel. The rigidity, according to Schweydar (1420), amounts to $6.8 \cdot 10^{11}$ cgs. for the crust; for the core, to $19.7 \cdot 10^{11}$ cgs. An easily flowing magmatic layer can be present at no depth within the earth. The speed of propagation of earthquake waves also leads to similar results relative to the rigidity of the earth. Summaries of our present knowledge on the rigidity of the earth, and its dependence upon the depth of the formations concerned, are given by Prey (1258, pp. 176–90), Shida (1439), Gutenberg (611, p. 62 *et seq.*). This rigidity applies, however, only to forces acting for relatively short periods of time. For deforming forces

which act uniformly through thousands of years, the earth appears to be plastic.

Isostasy.—If a complete relative mobility, according to the degree of fluidity, could be assigned to the masses of heterogeneous density which make up the earth, then similar cones drawn from the center of the earth to the surface would contain equal masses in a condition of equilibrium (if the effects of rotation are disregarded); the pressure must be completely and entirely compensated and hydrostatic equilibrium must prevail. In the uppermost formations, however, such an extensive mobility certainly does not exist, so that there are disturbances of equilibrium in these formations due to the combined effect of masses of different density and of differences in elevation. On the other hand, all conjectures point to the fact that near a depth of 100 km. the plasticity of the formations there present is so great that asymmetry in the distribution of pressure may have been already adjusted in the course of geologic time. According to Airy (12), Pratt (1253) (*cf.* also Bowie (228), Heiskanen (683, 684), Berroth (180*a*, p. 433 *et seq.*), Jeffreys (762*c*), Ansel (613*d*, p. 69)) a state of equilibrium has there been established, so that on each square kilometer of surface the same pressure is exerted, and thus, if the gravity differences are considered independent of the height, an equal mass rests. If this mass has a smaller cross-sectional density than the mean value for the entire upper crust of the earth, then the mean elevation above sea level of the mass in this region is correspondingly higher. If the density of the solid rock formations is greater than the average value, then there results a corresponding depression which is filled with the comparatively light water of the ocean or with air. A condition of the earth's crust in which the pressure at a definite depth is completely compensated is called, according to Dutton (370, 371), an *isostatic* condition. At the depth below sea level at which the adjustment is complete, lies the *surface of isostatic compensation.* Measurements of the force of gravity on the surface, and determinations of plumb-line deviations, etc. have shown that the earth's surface comes very near to such an isostatic condition. Reference only can be made here to the very comprehensive literature on this important question, especially on the application of isostatic considerations in geologic investigations over large areas of the earth's surface. Here special mention should be made of the work of Helmert (687, 692, 694, 695), Hayford

(650), Tittmann and Hayford (1543), Niethammer (1165), Prey (1256, 1257*a*, 1258, p. 138 *et seq.*), Putnam (1258*b*), Barrell (100*a*), Bowie (223, 225, 228*a*, 229, 231, 232), Alessio (19), Burrard (277), Kemp (804), Washington (1579), Hayford and Bowie (651), MacMillan (1022), Crostwait (323), Köppen (858*c*), Meissner (1078*a*), Born (205, 206), Lawson (925), Knopf (820), Hammer (633), Kossmat (861*a*), Schweydar (1425*a*).

A complete isostatic mass conpensation can, nevertheless, be associated with large variations in the curvature of the geoid surface, and in the value of the force of gravity, a fact which occasionally is not sufficiently considered. The potential due to the force of gravity depends upon the manner in which the masses within the uppermost crust of the earth, above the surface of isostatic compensation, are geometrically arranged, because the attractive effects of these masses, relative to the point at which the measurements are carried out, depend upon the squares of their distances. An excellent example of this fact is shown by the gravity disturbances on the coasts of the continents in comparison with a sea in isostatic mass arrangement. The mathematical theory is given by Schiötz (1365, 1366) and by Helmert (694). Figure 8 represents the gravity disturbances Δg along a profile perpendicular to the longer direction of a straight coast line. The mean density of sea water is assumed as 1.03; that of the solid subsoil as 2.83 (the latter is thus somewhat higher under the bottom of the sea than under the continents). The surface of isostatic compensation lies at 100 km. under the surface of the sea. The depression v of the continental border (strongly exaggerated in the figure) is assumed as $1° 9''$ (cotg. $v = 50$) as it corresponds somewhat to actual relations, and the depth of the sea next to the slope is taken as 4,000 m. as compared with a continent lying almost at sea level.

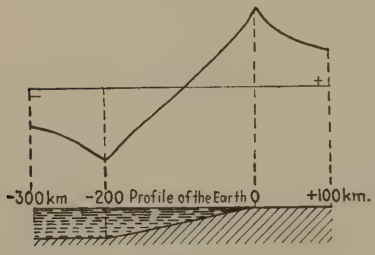

FIG. 8.

Zeil (1657) is of the opinion that the erosion of the continent and the filling up of the sea must bring about an isostatic gravity difference. These will be compensated in large part, however, by secular elevations or depressions (*cf.* Bowie 232*b*). Meissner (1077*a*) demonstrated by isostatic reduction of gravity measure-

ments at numerous coastal stations that coasts of the Atlantic type are usually isostatically compensated. On the other hand, in the case of coasts of the Pacific type, this compensation, in general, does not exist (see also Wolff 1643*a*). Wegener (1592) presents the view that the continental masses consisting preeminently of primordial rock (gneiss) of a mean density $\sigma = 2.6 - 2.8$ (Sial) float, as it were, on the basaltic ferruginous plutonic rock with a mean density $\sigma = 2.9 - 3.3$ (Sima), and effect isostatic compensation by plunging their relatively light roots correspondingly deeper into the Sima (see also Ansel (53), Schwinner (1426*a*), and Gutenberg (611, p. 90 *et seq.*)).

Born (205) designates the geoid and gravity disturbances which might possibly appear in actual complete isostasy as pseudo-isostasy. The possibilities of this pseudo-isostatic mass arrangement in the crust of the earth must not be overlooked, especially in investigations into the connection between regional gravity disturbances and the geologic structure of the deeper subsurface. In spite of the extremely interesting results of this study, space forbids going into the subject in more detail. Reference must again be made to the appropriate literature given above, especially that having to do with smaller areas such as come into consideration in the work of applied geophysics in mining, underground, and hydraulic engineering; complete isostasy, according to Bowie (226, 227, 232), may be assumed with sufficient approximation so that the smaller folds in the level or equipotential surface of gravity, as produced by salt domes, ore deposits, faults, etc., may generally be considered without regard to the question of general isostasy.

Reduction of the Gravity Values to the Geoid of Reference.—In the application of gravity measurements to practical geologic investigations, it is important to give the most careful consideration to the following circumstances:

1. Influence of the elevation of the place of observation above sea level.

2. Gravitational effect of the sheet of rock between the place of observation and the geoid surface of sea level.

3. Configuration of the surface of the earth in the vicinity of the point of observation.

In order to correlate the immediately observed (relative) values of the force of gravity at different points, and to be able to draw conclusions on the structure of the unknown deeper

subsurface, these three influences must be calculated and taken into consideration as corrections (*e.g.*, Berroth 180*a*, p. 458 *et seq.*).

The reduction of gravity on account of height above the sea, corresponding to the decrease of the force of gravity with the square of the distance, is equal to $\frac{2h}{R} \times g$, where h is the height of the place of measurement above sea level, and R the radius of the earth for the latitude under consideration. Since the influence of the latitude, however, is always very small, one can take this as 0.000,308,6, according to Helmert (694), for practically every latitude.

The space between the sea level and the surface of the earth at the point of observation, however, is not empty, but filled with rock whose gravitational effect must be taken into consideration if one wishes to think of the point of observation as transferred to sea level. First, let it be assumed that the ground is level around the place of observation. In level areas, the correction on account of the attraction of this sheet of rock, according to Bouguer (218), Messerschmidt (1094), Helmert (694), Bourgeois (219), Prey (1258, p. 133 *et seq.*), may be considered with sufficient accuracy as equal to

$$\frac{3}{2} \cdot \frac{\sigma}{\sigma_m} \cdot \frac{h}{R} \cdot g,$$

where σ is the mean density of the sheet of rock and σ_m the mean density of the earth $= 5.505$. This expression is designated as *Bouguer's reduction.*

Finally, one must still consider the "terrain reduction" which is caused by elevations above the horizontal through the point of observation and by valleys below it, and which always diminishes the measured values of gravity. The calculation of the terrain correction is a very tedious task. The region about the station is divided into quadrangles, according to Peters (1222*a*); or, as, for instance, Messerschmidt (1094, p. 122 *et seq.*), or Helmert (694, p. 106 *et seq.*) explains, it is better to divide it into separate prisms or sectors by means of concentric circles with rapidly increasing radii (of about 0.5, 1, 1.5, 2, 3, 4, 6, 8, 11, and 15 km.), and by radii (4 to 16) regularly placed relatively to one another. The mean height of these sectors is ascertained from accurate charts. (Great irregularities in the

topography in the immediate vicinity of the observing station must be given special consideration.) The multiplication of the volumes thus obtained by the mean density of the rocks existing there gives the magnitude of the mass, whose vertical component of attraction at the point of observation is then calculated. Isolated mountains of regular form (volcanic cones) can also be estimated geometrically as to their contents, and placed in the calculations.

While this "terrain correction" and the height above the sea must continually be taken into consideration in the comparison of gravity measurements at different places, in the case of Bouguer's correction the purpose of the comparison must be looked into, since, according to the purpose in view, the lower limiting surfaces of the prisms are frequently chosen in different manners. Bouguer (218) referred his correction to sea level. Hayford (650), as well as Tittmann and Hayford (1543), Hayford and Bowie (651), used as a surface of reference the isostatic surface assumed to be at a depth of 113.6 km., an example which was also followed by Bowie (223, 224, 229), Helmert (695), Meissner (1078), with, in part, other depths for the isostatic surface. Comparisons for other purposes demand other positions for this surface. See, for instance, Borras (211), Brillouin (246), Heiskanen (683).

Publications of relative-gravity measurements usually give the observed value g, the value reduced to sea level g_o, or the value according to Bouguer g_o'', also corrected relative to the attraction of the rock strata lying above sea level. If, then, the normal value for the true height γ or for the sea horizon γ_o, reckoned according to the position of the place of observation on the normal geoid surface, is subtracted from g_o'' there is obtained the gravity disturbance for the place of observation under consideration—in which, however, no attention has yet been paid to the land form and to the kind of isostatic compensation in the region investigated. Borras (211) gives extensive compilations of the gravity disturbances $g_o'' - \gamma_o$ with and $g_o - \gamma_o$ without Bouguer's correction. Additional data on the distribution of gravity on the surface of the earth for different regions are found in Kossmat (861), Born (205, 206) (Germany); (206*a*) (Iberian peninsula); in Bourgeois (219), Bowie (230), Deeke (340), (Apenines); (341) (Black Forest); (339) (Pomerania); Bowie (223*a*) (United States of America); Esclangon (434, 435)

(S. W. France); Haid (627) (Baden); Koch (824*a*) (Württemberg); Heim (681) (Switzerland); Helmert (689) (Tyrolean Alps); Heiskanen (684*a*) (Norway); Johansen (772) (Bornholm, Fünen); Prey (1256) (Eastern Alps); Ricco (1292) (Calabria, Sicily); von Sterneck (1484) (vicinity of Lake Balaton); Zachariae (1654) (Denmark); Krenkel (872) (East Africa) (872*a*) (Red Sea); Kohlschütter (851*a*) (East Africa); Ansel (53), Schwinner (1426) (Alps); Burrard (276), Oldham (1196*a*), Hayden (649*a*), Morley (1136*b*) (India); Heim (680) (Wallis, Switzerland). Von Sterneck (1485) describes observations underground (in the Tauern Tunnel).

The calculation of Bouguer's correction, and isostatic computations in general, require an estimation of the density of rock masses and their distribution at greater depths on the basis of similar data on formations near the surface. Table II (see page 43) contains the average densities for many rocks, as well as for some other important materials.

In using this and later tables for physical properties of different materials, it should be remembered that the general, and especially the customary, petrographic designations of materials and rocks are chosen from entirely different points of view from that which would be important and characteristic in the estimation of their relations to the problems of applied geophysics. If one wishes further to subdivide the various rocks, etc., relative to their physical relations in a manner effective for the carrying out of geophysical prospecting, one must limit one's self to reproducing in very great numbers chance-measured values of purely local importance, which possess relatively little significance for the estimation of the physical characteristics of similar rocks, etc., in other surroundings. Hence, the tables are limited to data of average and limiting values, so far as such are known. In the estimation of the physical constants of materials in a new region of investigation, one must attempt, for the time being, to secure these valid material constants from the regional literature or by special measurements. The following tables will, and can, afford only a general survey and must be used with careful criticism.

TABLE II.—DENSITIES OF VARIOUS ROCKS AND OTHER HEAVIER MATERIALS

	Mean value	Limiting values
Agate	2.60	2.5 –2.8
Alabaster	2.66	2.25–2.87
Alabandite	4.00	3.95–4.04
Alum slate	2.46	2.34–2.59
Anglesite	6.34	6.30–6.39
Anhydrite	2.96	2.92–2.98
Anthracite	1.50	1.30–1.80
Antimonite	4.60	4.40–4.70
Argentite	7.28	7.2 –7.34
Argillite (clay slate)	2.8	2.76–2.88
Arsenopyrite	6.1	6.0 –6.2
Asphalt	1.3	1.1 –1.5
Barite	....	4.3 –4.6
Basalt	3.0	2.7 –3.3
Basalt lava	2.30	2.05–2.46
Bauxite	....	2.0 –3.0
Beton	....	1.51–2.54
Bog iron ore	2.6	
Bornite	5.0	4.9 –5.2
Braunite	4.79	4.75–4.82
Calamine	4.30	4.10–4.50
Calcareous tufa	1.64	1.57–1.71
Calcite	2.72	2.60–2.78
Carnallite	1.60	
Cassiterite	6.95	6.85–6.98
Cerussite	6.57	6.47–6.72
Chalcopyrite	4.2	4.1 –4.3
Chalcocite	5.78	5.5 –5.8
Chalk	2.2	1.8 –2.6
Clay	2.2	1.8 –2.6
Cobaltite	6.5	6.0 –6.1
Corundum	3.95	3.9 –4.0
Cuprite	....	5.7 –6.2
Cyanite	2.13	
Diabase	2.95	
Diorite	2.85	2.70–2.95
Dolerite	2.85	2.45–3.09
Dolomite	2.75	2.44–2.90
Earth, loose, dry	1.20	1.12–1.28
Earth, loose, fresh	1.40	
Earth, stamped, dry	1.80	1.60–1.92
Earth, stamped, fresh	2.10	2.10–2.20
Feldspar	2.55	2.53–2.58

TABLE II.—(*Continued*)

	Mean value	Limiting values
Flint	2.70	2.58–2.80
Fluorite	3.15	3.10–3.20
Foliated coal	1.35	1.20–1.50
Gabbro	2.95	2.90–3.00
Galena	7.65	7.51–7.76
Glance coal (anthracite)	1.35	1.20–1.50
Gneiss	2.60	2.40–2.90
Granite	2.75	2.46–3.05
Graphite	2.30	2.17–2.32
Gravel, dry	1.9	1.8 –2.0
Gravel, wet	2.0	
Greenstone	2.95	2.90–3.0
Gypsum	2.25	2.17–2.31
Hausmannite	4.86	
Hematite	4.7	4.5 –4.9
Hematite, specular	5.24	5.16–5.30
Heavy spar	4.5	4.42–4.68
Hornblende	3.0	2.6 –3.4
Ice (0° C.)	0.917	0.88–0.92
Iron	7.86	7.70–7.90
Kaolin	2.2	
Kermesite	4.6	4.5 –4.6
Kieserite	2.57	
Lava, basaltic	....	2.8 –3.0
Lava, trachitic	....	2.0 –2.7
Lead	11.34	11.20–11.44
Lignite	1.30	1.10–1.44
Limestone	2.7	2.3 –3.0
Limonite	3.67	3.40–3.95
Loam, dry	....	1.5 – 1.6
Loam, freshly dug	....	1.67–1.85
Magnesite	3.0	
Magnetite	5.16	4.96–5.40
Malachite	3.85	3.7 –4.0
Maganese ore, red	3.46	
Maganese ore, black	4.00	3.9 –4.1
Marble	2.70	2.52–2.85
Marcasite	....	4.86–5.03
Marl	2.40	2.3 –2.5
Melaphyre	2.64	2.6 –2.8
Mica	2.80	2.65–3.15
Mineral coal	1.35	1.2 –1.5
Molybdenite	4.6	4.44–4.80

TABLE II.—(*Continued*)

	Mean value	Limiting values
Nagelfluhe conglomerate	2.40	2.1 –2.7
Olivine	3.4	3.27–3.57
Pig iron	7.25	7.03–7.73
Pitchblende	....	8.0 –9.7
Porphyry	2.7	2.34–2.9
Potter's clay	1.7	
Psilomelane	....	4.13–4.33
Pumice	0.64	0.36–0.91
Pyrite	5.10	4.9 –5.2
Pyrolusite	5.03	4.7 –5.05
Pyrrhotine	4.8	
Pyrrhotite	4.55	4.54–4.64
Quartz	2.65	2.55–2.75
Realgar	3.4	3.24–3.60
Rhodochrosite	3.61	3.55–3.66
Rock salt	2.3	2.1 –2.4
Sand, dry	1.5	1.4 –1.65
Sand, moist	1.8	1.7 –1.9
Sand, wet	2.0	1.95–2.05
Sandstone	2.3	1.8 –2.8
Scheelite	6.04	6.02–6.08
Schist	2.67	2.65–2.70
Serpentine	2.6	2.4 –2.7
Siderite	3.8	3.7 –3.9
Silica	2.70	2.66–2.74
Silver ore, red	5.68	5.50–5.85
Smaltite	6.8	6.4 –7.3
Snow	0.125	
Sphalerite	4.06	4.03–4.08
Stannite	4.35	4.3 –4.5
Strontianite	3.62	3.60–3.63
Sulphur	2.00	1.92–2.07
Syenite	2.77	2.46–2.91
Sylvite	1.95	1.9 –2.0
Tetrahedrite	4.9	4.36–5.36
Tile masonry	....	1.4 –1.5
Trachite	2.6	
Tufa	1.3	1.3 –2.4
Tungsten-lead ore (Stolzite?)	8.18	8.10–8.24
Zincite	....	5.4 –5.7

Derivation of the Geologic Structure of the Uppermost Crust of the Earth from Gravity Measurements.—If, conversely, one

wishes to discover the unknown geologic structure of the subsurface from gravity measurements, then one must derive from the measured form of the level surfaces and from the distribution of the gravity values upon them, with due consideration of the probable general tectonic structure of the region concerned, quantitative conclusions on the position, form, and density of the objects sought (heavy ores, light salt masses, terraces in heavy basal formations because of faulting); from the calculated density one infers the kind of rock in the existing subterranean masses. Thus the problem of gravity measurements is placed within the bounds of applied geophysics (see Carlberg (284), White (1604), Gilbert (549), Ampferer (35*a*), Messerschmidt (1090), Prey (1258, p. 132 *et seq.*)).

A problem of this kind follows, for instance, from the foregoing data on the variation of the value of the gravitational force perpendicular to the coast line of a continent, if the depth of the sea is regarded as unknown; then this depth of the sea and the inclination of the slope of the sea bottom may be determined from the variations in the value of gravity. As an example, there may be cited the determination of the form of the geoid in the Harz by Galle (517). (See also Hammer (632), in which the plumb-line deviations are derived.) The heavy eruptive rocks of the Upper Harz cause a ridge on the geoid surface. There are reports by Schweizer (1416) and Sludski (1453, 1454) on gravity anomalies at Moscow; by Kowatscheff (867) on the form of the geoid in Bulgaria; and by Helmert (690) on the attraction anomaly along the lines of Kolberg-Schneekoppe and the Berlin meridian. Mention should also be made of the investigations of Bourgeois (220), Burrard (275, 276), Fisher (452), Pratt (1252) (India), and Close (309) (Andes). The connection of the lines of equal variation of gravity with the subsurface structure is treated by Gilbert (549). Hecker (664) refers to the value of systematic gravity measurements for a knowledge of the mass distribution in the earth's crust. The most suitable form for the representation of gravity anomalies is that in which the origin of the gravity anomalies is considered as occurring in a formation of density (θ) at sea level, whose thickness always corresponds to the magnitude of the disturbance. If one then draws the lines of these "ideal disturbance layers" for equal difference of disturbance, one obtains a clear picture of the distribution of the gravity disturbances in the region under consideration, as may be seen, for

instance, in Fig. 9 for the southern part of Baden and Württemberg, after Haid (627).

An example of the practical application of pendulum measurements to the detection of salt domes in the subsoil has been given by Berroth (180*b*) on the salt dome of Oldau-Hambühren which has served for so many geophysical investigations. However, for the present it seems very doubtful whether, apart from individual exceptional cases, this method shows technical, and especially economic, advantages over the other geophysical methods applicable to the problem.

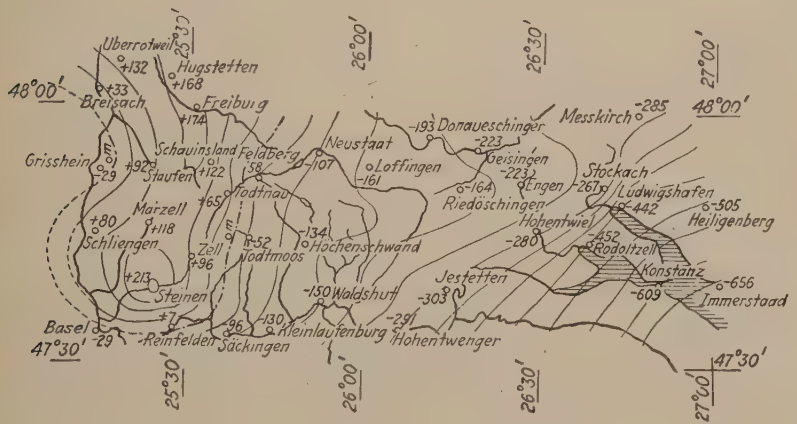

FIG. 9.

The Reduction of the Torsion-balance Measurements to the Geoid of Reference.—In applied geophysics, the determination of the form of the level surfaces and the gradients of the force of gravity by the torsion balance is of especial importance.

In order to use the data which are obtained by the torsion balance, one must remove the effects of the visible known configurations of the surface of the earth, from the observed values, whose derivations, measurement, and significance are shown individually on page 16.

For the calculation of corrections which are applied to the magnitudes measured by means of the torsion balance, relative to the visible land forms, the horizon of the place of measurement is generally used as a reference surface. To this horizon are referred the subterranean-disturbance values obtained after the application of these corrections (von Eötvös (399)). The correc-

tions consist of two parts: the variation of Bessel's or Helmert's normal geoid at the point of observation from the spherical form; and the disturbing effect of the deviations of the true surface of the earth from the horizontal. In practice, the latter effect is subdivided into the influence of surface irregularities to within 100 m. of the point of observation. These are determined by taking elevations. On the further surroundings, out to a distance of 1,000 m., elevations can be obtained from topographic maps (topographic correction).

The elevations of the more distant regions up to 30 to 40 km. distance can also be obtained from the topographic maps (cartographic correction). The topographic effect of the terrain can be calculated according to von Eötvös, if the region is divided into prismatic sectors, by concentric circles of rapidly increasing radii (for instance, 5, 10, 20, 50, 100, 1,000 m.) and by radii (for example eight) spaced uniformly with respect to each other. The mean height and the rock density of each sector are estimated as accurately as possible, and their relative effect on the magnitude concerned is calculated. For calculating the cartographic effect, the surrounding area is divided into segments (*e.g.*, 36) within which horizontal formations lie, and within which the distances may be obtained from topographic maps. The greater the distances from the point of observation, the thicker the formations which can be considered together. Help in these rather tedious and time-consuming correction calculations is given by Schweydar (1425), Numerov (1188*a*), Heiland (676), Schumann (1409*a*), and Ansel (613*d*, p. 528 *et seq.*). Holst (738) refers to the advantage of a reduction method by which the gravitational field of the topographic element is calculated individually and the disturbance for each point of measurement is obtained by summation of the effects of the individual elements. The great difficulty in these reduction calculations lies in the correct insertion of the density of the disturbing mass. Formal mathematical accuracy is most urgently desirable in the consideration of land forms in reduction calculations, as long as there is no great certainty on the geologic structure of the elevated masses and on the distribution of density in them.

Examples of Investigations with the Torsion Balance.—A number of examples of the application of the torsion balance can now be considered. First, Fig. 10 shows an ideal profile, according to von Eötvös (401), of the effects of alternating deep

layers of heavy basal formation with the density 2.6 under a lighter covering of density 1.8. Along the surface of the earth the distance is recorded in kilometers. The scale on the right border gives the depth of the limiting formation in units of 50 m.; at the 16-km. surface point, the bounding formation has a depth of 1,000 m.—its greatest depth. Curve 1 indicates the magnitude $d^2U/dndz$ (n is assumed in the direction of the profile), *i.e.*, the change of the force of gravity (dU/dz) in the direction

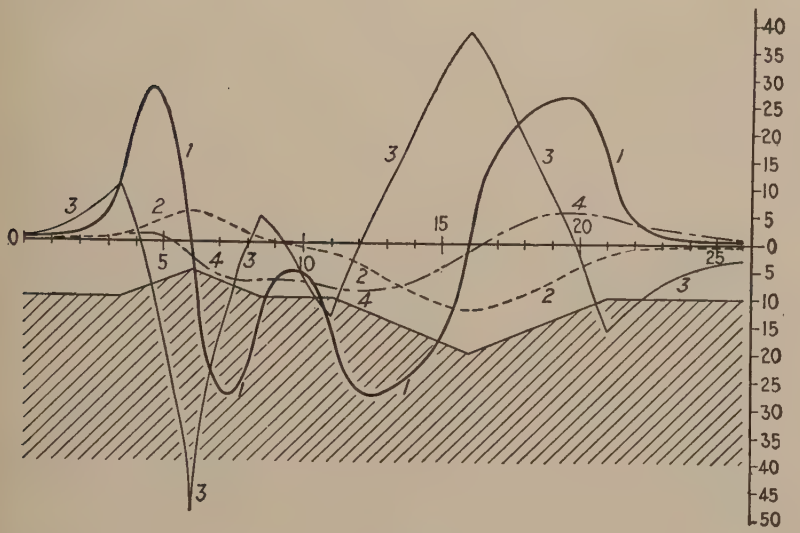

FIG. 10.

of the profile; 2, the gravity anomaly itself; 3, the difference $\frac{d^2U}{dn^2} - \frac{d^2U}{ds^2}$ (s = the direction perpendicular to the profile); 4, dU/dn. The quantities 1, 3, and 4 are given in 1.10^{-9} c.g.s. units, the quantity 2, in 0.001 cm./sec.^{2}, so that the ordinates of the different curves correspond to about similar accuracies of observation. The plumb-line deviations, which correspond to a position near the 0-km. point, are given in Table III, because the deviations are too small to exhibit the shape of the curve if plotted to the scale used in the figure.

TABLE III

Distance, kilometers	Plumb-line deviation in seconds	Distance, kilometers	Plumb-line deviation in seconds
0	0.0	14	1.5
1	0.0	15	0.9
2	−0.1	16	0.4
3	−0.2	17	−0.3
4	−0.3	18	−0.8
5	−0.1	19	−1.2
6	0.5	20	−1.2
7	1.3	21	−1.0
8	1.5	22	−0.7
9	1.5	23	−0.5
10	1.5	24	−0.4
11	1.7	25	−0.3
12	1.8	26	−0.3
13	1.7		

The superiority of torsion-balance measurements over those of the invariable pendulum is shown by the curves. With increasing depth, the transition formation keeps almost the same depth relations in curve 2, while curves 1, 3, and 4 become flatter. This indicates that the torsion-balance measurements are especially adapted for objects near the surface, while the gravity measurements offer special advantages for the estimation of the major structural lines of greater depths.

The effect of a step in the denser basal formation (*e.g.*, of a fault) on the gradient, $d^2U/dzds = dg/ds$, is shown in Fig. 11, after von Eötvös (399, p. 390). The density σ of the surface portion is here assumed as 2 to 2.5. The heavy subsurface mass rises at the step from 1,500 m. to 500 m. below the surface of the earth. For a point N on the surface which is distant r_1 and r_2 from the upper and the lower edge of the step,

$$\frac{dg}{ds} = 2\varkappa(\sigma' - \sigma) \log \frac{r_2}{r_1}$$

($\varkappa$ = the gravitation constant).

A somewhat complicated case of the gravity distribution in the subsurface is treated in Fig. 12, after Eötvös (399, p. 391). Curve *a* indicates the course of the magnitude $d^2U/dzds = dg/ds$; curve *b*, the course of the magnitude of curvature,

$$\frac{d^2U}{ds^2} - \frac{d^2U}{dn^2}.$$

Figure 13 gives an example for the case of an ore body (very elongated and perpendicular to the plan of the diagram) of rectangular cross-section, after Schweydar (1421, p. 160). The density of this body is assumed as 5.5; that of the basal formation as 2.6; its cross-section 500 × 1,000 m.; and its upper surface lies 1,300 m. below the

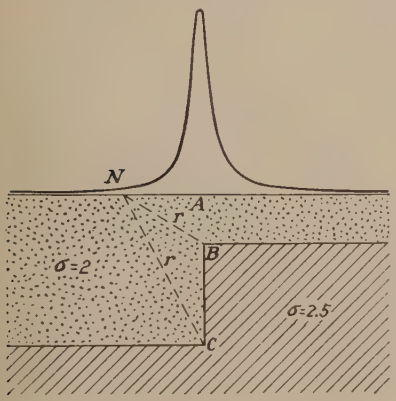

Fig. 11.

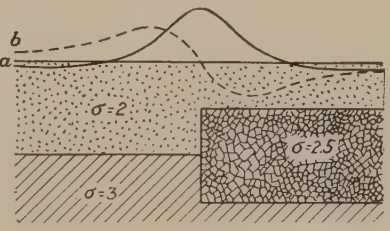

Fig. 12.

surface of the earth. The ordinates of the curve give the horizontal gradients of the acceleration of gravity (dg/ds), while the position ordinates indicate that the gradients point toward the right side. The asymmetry of the gradients over a superficially oblique disturbing body with density 2.3, within a basal

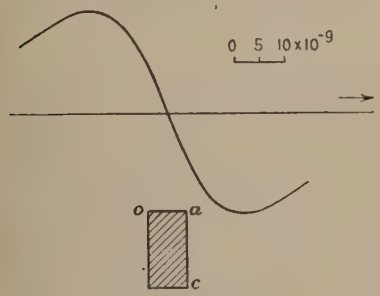

Fig. 13.

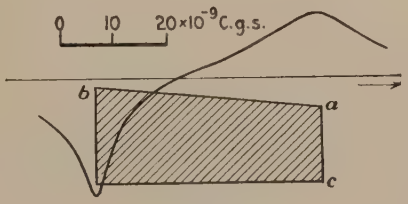

Fig. 14.

formation of density 2.6, whose two upper edges lie 100 and 400 m. deep, and which ends with a horizontal boundary at 1,400 m., is shown by Fig. 14, after Schweydar (1421, p. 160). In nature, similar forms with corresponding density distribution are found in salt domes. The calculation from torsion-balance meas-

urements of the depth of the mass, which produces the gravity anomaly, is also treated by Meisser (1069), Mader (1023), Inglada (770), Ansel (613*d*, p. 548 *et seq.*).

Some additional examples of measurements which can be carried out with the torsion balance will follow. They will be premised by some classic measurements in Hungary under the direction of R. von Eötvös.

Figure 15 shows, according to von Eötvös (402), a section from the Hungarian lowland at Kecskemet, where a short time previously strong earthquakes had occurred, and whose isoseists (lines of similar quake strength) are recorded. The isoseist of greatest quake strength bears the degree-number 10. At the point designated by a small circle, the torsion-

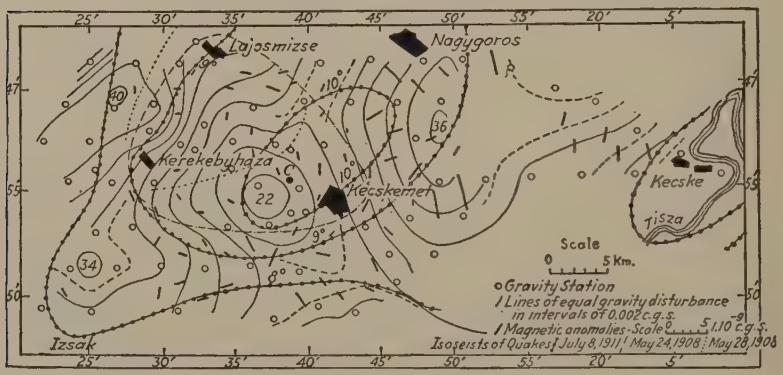

Fig. 15.

balance measurements were made. The horizontal gradients of gravity are not shown, for the sake of clarity; but only the lines of equal gravity disturbance (isanomalies), which are always vertical to the direction of the gradients, and whose interval is inversely proportional to the magnitude of the gradient, are represented. If one assumes, as seems warranted geologically, that lighter sediments lie above a heavier basal formation, then the isanomalies, also called isogams, become lines of equal depth (formation lines) corresponding to the boundary between the kinds of rock. The isogams then show that the surface of the heavy basal formation west of Kecskemet forms a kind of funnel or crater which is enclosed by a wall formation, all buried deeply under more recent formations. According to the isoseists, the earthquake impulses seem to

emanate from the crater. Von Eötvös, while making his gravity measurements, also measured the distribution of the

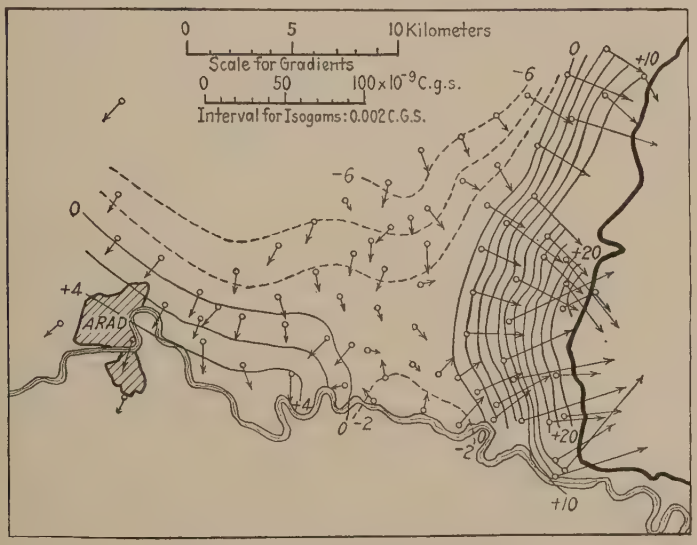

FIG. 16.

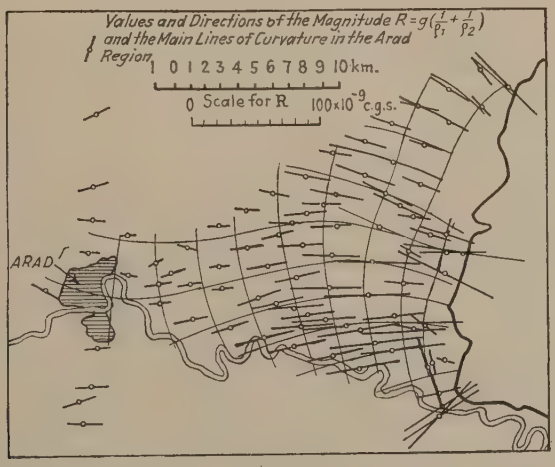
Values and Directions of the Magnitude R = g(1/ρ1 + 1/ρ2)
and the Main Lines of Curvature in the Arad
Region
1 0 1 2 3 4 5 6 7 8 9 10 km.
0 Scale for R 100 x 10⁻⁹ c.g.s.
ARAD

FIG. 17.

earth's magnetic field, to structure of which the striae in Fig. 15 refer, and whose importance in the convenience of handling methods of terrestrial investigations will be spoken of later.

The district east of Arad (now just within the Roumanian border) on the eastern border of the Hungarian plain, has been worked out by von Eötvös (399) in such great detail as to constitute a textbook example. Figure 16 shows the direction and magnitude of the horizontal gradients of the force of gravity and the isanomalies as above defined. Figure 17 also gives the accompanying distribution of the magnitude

$$R = g\left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right),$$

as well as the direction of the main curvature of the level surface. As this alone is not sufficient, von Eötvös (399) further gives the method of deriving with great accuracy, from the magnitudes determined by the torsion balance with the addition of the differences of plumb-line deviation, found astronomically-geodetically for two points of the region, the form of a level surface from point to point as long as the investigated region does not differ too much from a plane. Von Eötvös also made relative gravity measurements at some points. The results of these gravity measurements are exhaustively discussed within reference to torsion-balance measurements made at the same place. From this material, the two profiles, (Figs. 18 and 19,) have been derived, under the assumption that the deeper subsurface shows the density $\sigma = 2.6$, the younger, upper, covering a density $\sigma = 1.8$ g. per cubic centimeter (see also Eggert (380*d*) and Inglada (770)).

On the ice of a frozen lake, the calculation of the torsion-balance measurements is simplified by the fact that the disturbances caused by inhomogeneity of the subsoil do not fall in close proximity to the place of observation. Von Eötvös (400) tested his method on the ice of Lake Balaton. From the measurements on frozen Lake Titi, Holst (738) derives the profile of the lake bottom and finds a satisfactory agreement of his results with the profile obtained from soundings.

Valuable service has been rendered by the torsion balance in practice in search for salt domes (which consist of especially light material), in north Germany, Poland, Roumania, and Texas, and in the establishment of the position and extent of large deposits of heavy ore, especially iron ore; Lasareff (913) also shows that the amount of ore present can be estimated by this means. With deposits of other still heavier minerals (accord-

ing to Table II), in general, the masses present are usually not large enough to exert a sufficient effect on the structure of the field of gravity on the surface of the earth. In such cases, the torsion balance can be of great service in giving the lines of

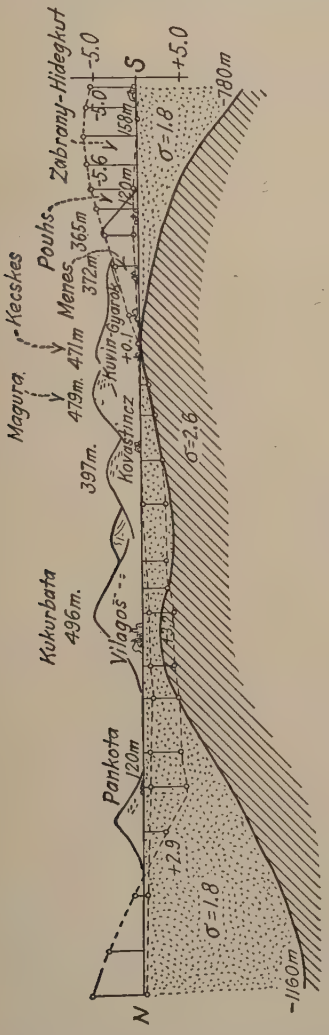

Fig. 18.

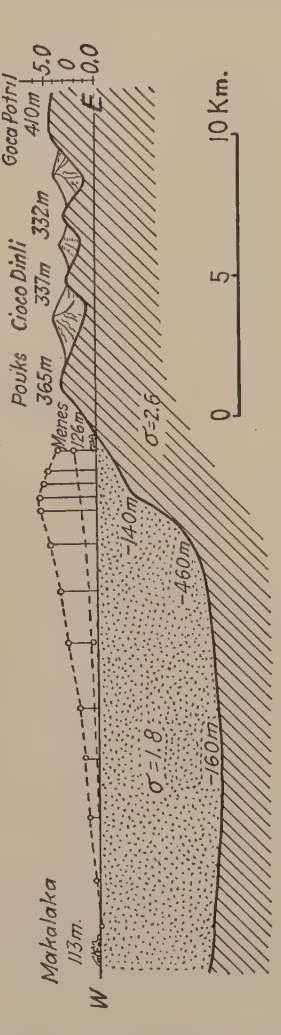

Fig. 19.

direction relative to the general tectonics of the region concerned, provided the length of time required for the torsion-balance measurements and the resultant high costs of operation do not exclude its application.

Examples of the application of torsion-balance measurements to the search for salt domes are given notably by Schweydar (1421), Shaw (1433), Fulda (493), Birnbaum (189). Birnbaum also reports on torsion-balance measurements made underground for the determination of the direction of the strike in important mining projects. As an example of the application of the torsion balance to salt above ground, the results of the measurements in the region of the Prince Adalbert Potash Works,

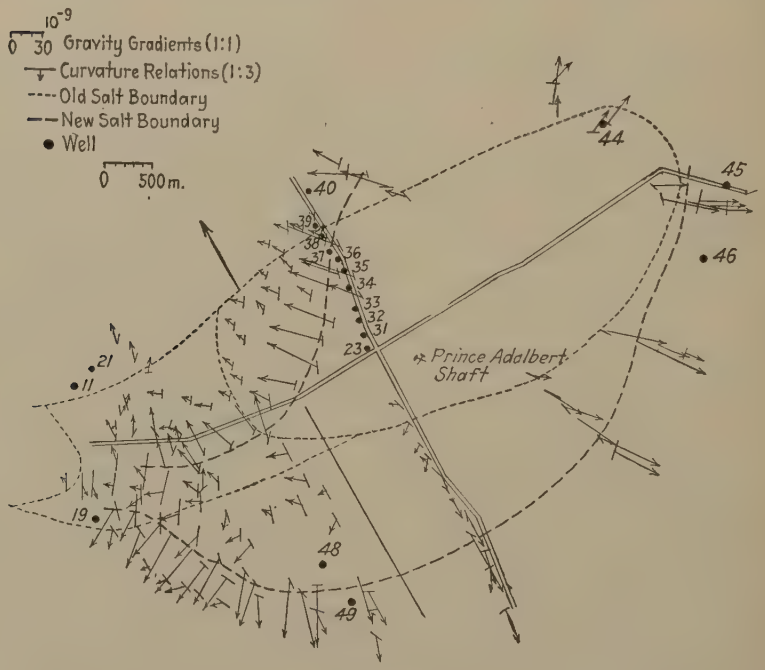

Fig. 20.

southwest of Celle, are given in Fig. 20, after Schweydar (1424, p. 363). This salt dome has likewise been measured to somewhat equal extent by means of magnetic, electric, and seismic methods. The results of these four methods were in astonishingly close agreement, especially in regard to the details of the outline, the depth, position, and angle of incidence of the flanks. The special peculiarities of the methods, depending upon different physical properties, supplemented each other in the most fortunate manner, and, moreover, in the most different directions.

Unfortunately, the results of these observations have not, up to the present, been published. The determination of the exact configuration of salt domes is, however, of great importance for the valuation of oil lands, since the oil-bearing formations are limited in the majority of cases to the flanks of such salt domes (*cf.* also 27*a*, 28, 29, 837).

An example of the application of the torsion balance underground is shown by Fig. 21, likewise after Schweydar (1424, p. 361). Here the main mass of anhydrite, which has the density 3.0, is adjacent to rock salt with lesser density 2.2. In the right portion of the figure the gradients of the force of gravity also have directions corresponding to this density distribution. The large gradients at the left, however, do not entirely agree with the horizontal cross-section through the formations, so

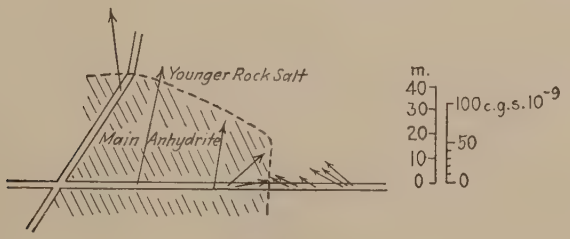

FIG. 21.

that either this has been incorrectly interpolated or the higher- or deeper-lying parts of the salt layers influence the magnitude and direction of the gradients. In measurements with the torsion balance under the ground, therefore, the geologic explanation of the results must be made with caution. The influence of the hollow spaces (usually very irregular in form) in the vicinity on the form of the gravitational field at the point of observation is rather difficult to calculate, but usually is of less importance.

Gornick (574) and Quiring (1266) are concerned with the application of the torsion balance to the search for iron ores. From the report of the latter, results of observations on an iron-ore seam in Siegerland are shown in Fig. 22, although the number of the measurements is not sufficient to prove the general adaptability of the torsion balance for exploring such small, seamlike occurrences of heavy ore lying in highly mountainous countries.

The measurement of adjacent large masses by means of the torsion balance is treated by Mader (1024).

The general importance of torsion-balance measurements in the search for oil deposits is discussed by Craig (320). Examples of the application of torsion balance measurements to the problem of coal mining and general tectonics are given by von Eötvös (400), Holst (737), Schumann (1406, 1407, 1408, 1409), Quiring (1267), Angenheister (51*c*), von Boeckh (195, 196), Nikoforov (1166), Kober (822), Mader (1023), Laska (917, 918). Rybar (1334) treats of torsion-balance measurements relative to the finding of mineral deposits in general.

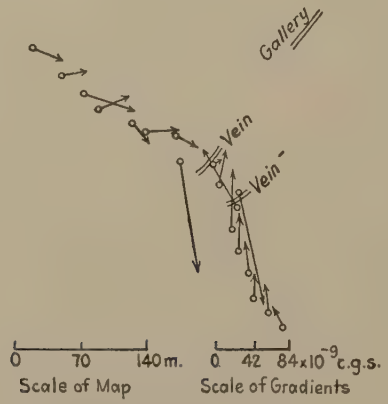

FIG. 22.

Measurements of the radius of curvature in the Simplon Tunnel by means of a gravity balance of the first kind were instituted by Brillouin (247). Very noticeable deviations from the normal values for the point of observation were found, which were ascribed to the influence of the overlying mountain masses.

The possibility of observing the behavior of an intermittently active volcano by means of the torsion balance, in order to predict future outbreaks of activity from the mass displacement in its interior, were discussed by von Eötvös (398).

Plumb-line Deviations.—Reference will be made in a few words to the results of the discussion of the determinations of plumb-line deviations for the purpose of analyzing the subsurface density distribution. Comprehensive data have been assembled by Börsch (212), also in collaboration with Krüger

(213), by the latter alone (873), and by Helmert (688, 690), especially for German stations. The influence of the visible mass of the Harz on the plumb-line deviation was investigated by Messerschmidt (1092) and Haasemann (619*a*). However, this example was comprehensively worked out for utilization of plumb-line deviations in the determination of the geoid form in the Harz by Galle (517); Hammer (632) examined this work in a detailed report. Reports were made by Schweizer (1416) on the plumb-line deviations in the disturbed region of Moscow; Bourgeois (220) reported on that in the Sahel d'Algier. The great plumb-line disturbances at the foot of the Himalayas have found numerous compilers, among others, Burrard (275, 276), Oldham (1196), and Fisher (452). For the Andes, Close (309) gives corresponding data. Helmert (690; 694, p. 162 *et seq.*) treats, in detail, the analytical connection between the areal distribution of gravity disturbances which are derived from ideal disturbance formations at sea level and the plumb-line deviations from examples at hand, with previously published data. Conversely, Berget (169*a*) shows how the average density of the whole earth can be calculated from the plumb-line deviations over a fault with known throw and with known density of the two formations faulted opposite one another.

Von Eötvös (399) shows in the most detailed manner how one can calculate, from small astronomically-geodetically obtained plumb-line deviation differences, the plumb-line deviations at intermediate points by torsion-balance measurements, and uses his measurements east of Arad as an example of such an investigation. The results of such calculations are introduced in the profile, Figs. 18 and 19, as heavily stroked lines, while the plumb-line disturbances produced alone by the visible mountain masses on the eastern border of the Plain of Arad are given by thin lines.

CHAPTER III

MAGNETIC METHODS OF INVESTIGATION

The General Magnetic Field of the Earth.—A magnetic needle which is free to move in all directions under the influence of the earth's magnetic field adjusts itself in a definitely determined direction at each point on the earth. If the needle rotates only about a vertical axis, after the manner of a compass, then the angle which the line joining its magnetic pole (its magnetic axis) makes with the plane of the astronomical meridian is designated as the angle of declination or aberration of the magnetic needle *D*. If the accurately balanced needle is allowed to swing around a horizontal axis which is vertical to the plane of the magnetic meridian, *i.e.*, the plane perpendicular to the direction of the compass needle, the angle which the magnetic axis of the needle includes with the horizontal plane is designated as the angle of inclination *I*.

The magnetic force can be indicated geometrically at each point as a vector by an arrow which starts at the point of observation, and which, according to its direction and size, symbolizes the magnetic force. In order to associate the length of the arrows with the strength of the magnetic force (the intensity of the magnetic field), the scale also must be given. In contrast to the force of gravity which influences in the same way all bodies in proportion to their density, every body on which the magnetic force acts is polarized, and the diametrically opposite parts of the body are influenced in opposite directions. In a homogeneous magnetic field, however, no translatory force, but only a torsion moment, is exercised on any magnetized body, although in such a body the parts affected in magnetically opposite directions can be divided among themselves entirely at will.

In order to obtain a measure for the strength of magnetic effects, it has been determined that two magnetic poles of equal strength but acting in opposite directions, shall have unit strength (unit polarity) if they attract each other with the force of 1 dyne at 1-cm. distance from each other. (One dyne equals

$\frac{1}{981}$ of the force with which the earth attracts one gram.) The strength of a homogeneous magnetic field is, then, that force which is exerted on a unit magnetic pole, measured in dynes (1148, p. 32). The unit of strength thus defined has been named a "gauss" after Gauss (518, 519), the founder of this so-called "absolute" system of measurement. The 1/100,000 part of this unit, often used in terrestrial magnetism, is designated by γ.

The force exerted by the magnetic field of the earth on a unit pole is the total intensity T of the earth's magnetism; it acts in the direction given by declination and dip. The total intensity T may thus be resolved, within the plane of the magnetic merid-

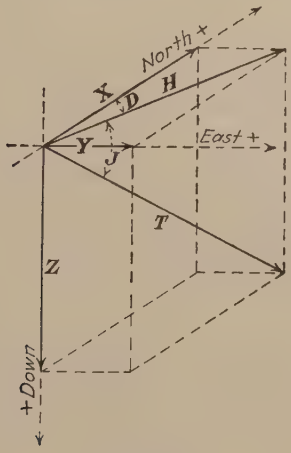

FIG. 23.

ian, into two components perpendicular to each other: the vertical intensity Z, and horizontal intensity H. The latter can then be resolved into a north-south and an east-west component, which are usually designated by X and Y. Figure 23 shows the relation of these different magnitudes to each other. The usual convention for signs is: D (the declination) is positive towards the east, I (the dip) is positive if the north pole of the needle is below the horizontal; X is positive towards the north; Y toward the east; and Z downward. H and T are always positive.

Three of these magnitudes always characterize the magnetic earth field at any point. For geographic and nautical purposes, the representation of the field is usually made by means of D, I, and H. For scientific purposes, and usually also in the dis-

cussion of geophysical measurements, the system of X, Y, Z is considered more convenient. The systems D, I, and T, or D, H, and Z have also been used to advantage occasionally in observations or calculations. For convenience in going from one system into the other, a number of the transformation formulæ which are most often necessary are collected here. These follow, without further discussion, from Fig. 23:

$$X = H \cdot \cos D, \quad Y = H \cdot \sin D, \quad Z = \quad \cdot \tan I = T \cdot \sin I;$$

$$H = \sqrt{X^2 + Y^2} = T \cdot \cos I,$$

$$T = \sqrt{X^2 + Y^2 + Z^2} = \sqrt{H^2 + Z^2} = \frac{H}{\cos I};$$

$$\tan I = \frac{Z}{\sqrt{X^2 + Y^2}} = \frac{Z}{H} \quad \tan D = \frac{Y}{X}.$$

Measurements of the strength of the magnetic field were carried out much later than those of declination and inclination—about the end of the eighteenth or the beginning of the nineteenth century. Their particular value was emphasized by von Humboldt (594, p. 523). It was Gauss (518, 519), however, who first learned to make the measurements in a constantly comparable manner on the basis of his system of absolute measurement.

The Time and Space Changes of the Earth's Magnetic Field.—The earth's magnetic field is always changing. The magnitudes determined for this field at any place change with time and they possess at the same point of time very different values along the surface of the earth. For practical purposes, it is often recommended that the momentary value of the magnetic force be regarded as the resultant of a normal value of its strength and direction (normal magnetic-force vector) and a component due to variation with time or distance (a disturbance vector). For further reference, there should also be established at the same time those relations through which the different values of such a disturbance vector, when determined, can be converted into one another. The deviations of the measured declination, horizontal and vertical intensity ΔD, ΔH, and ΔZ from the normal values D, H, and Z, are known by observation. The corresponding variations ΔT of the total intensity, ΔI of the dip, as well as ΔX and ΔY of the north-south or east-west components, are then given (as long as the variations are assumed as small) as:

$$\Delta T = \Delta H \cdot \cos I + \Delta Z \cdot \sin I;\ \Delta I = \tfrac{1}{2} \sin 2I \cdot \left(\frac{\Delta Z}{Z} - \frac{\Delta H}{H}\right);$$

$$\Delta X = \Delta H \cdot \cos D - \Delta D \cdot H \cdot \sin D;$$

$$\Delta Y = \Delta H \cdot \sin D - \Delta D \cdot H \cdot \cos D$$

finally,

$$\Delta Z = \Delta H \cdot \tan I + \Delta I \cdot \frac{H}{\cos^2 I},$$

and the total disturbance vector

$$\Delta T = \sqrt{(\Delta X)^2 + (\Delta Y)^2 + (\Delta Z)^2}.$$

The declination d of the disturbing force is given by $\tan d = \Delta Y/\Delta X$, and its inclination i by $\sin i = \Delta Z/\Delta T$. The horizontal disturbing force will be

$$\Delta H = \Delta T \cdot \cos i = \sqrt{(\Delta X)^2 + (\Delta Y)^2}.$$

While the areal variations of the normal distribution of the magnetic force form the real object of the magnetic methods in applied geophysics, the time variation must be carefully considered in the carrying out of such measurements, in order to be able to eliminate them by calculation from the sum total of individual observations which have been made at different times in the same magnetic investigation. Hence, the different kinds of time variations and their origin should next be discussed.

The Time Variations of the Earth's Magnetic Field.—The time variations may be divided into (1) periodic variations which follow certain laws relative to their appearance, and (2) sudden, irregular disturbances. With this difference as a basis, the registration of time variations, obtained in the magnetic observatories of the different countries, is daily separated into groups, according to whether the designated curves exhibit only changes of a slow periodic type (quiet days), a mixture of these periodic variations with a certain number of smaller disturbances, or an accumulation of irregular disturbances which blot out the periodic character of the curves entirely. The three designated types of magnetic activity are indicated in the above series by characteristic numbers 0, 1, and 2. On the point of view which is decisive for the assignment of the characteristic numbers, there are reports by Schmidt (1385), van Dyk (372), Ono (1202*a*), and Chree (302). Bartels (101) attempts to establish a simpler measure for this activity; he also deduces tables for the earth's

magnetic activity (101*a*). A collection of the characteristic numbers determined by magnetic observatories each day are published regularly by the observatory in De Bilt (Holland). An especially critical standardization is always requisite in daily field measurements of Type 2.

Periodic Disturbances.—Regular periodic fluctuations originate in the rotation of the earth on its axis as well as its revolution around the sun. Correspondingly, a daily and a yearly period appear in them, which can be indicated in the form of a curve for each element of terrestrial magnetism individually dependent upon the time. Such curves, based on the data of 1890 to 1900 for Potsdam, have been given by Nippoldt (1148). More recent values are given by Schmidt (1384, 1390). For the purposes of geophysical methods of investigation, the values of the daily variations occurring at the time of the observation can be taken with sufficient accuracy from these curves in almost all cases within Germany. In other countries, if necessary, the corresponding curves must be obtained from the nearest magnetic observatory.

According to Barlow (96), Schmidt (1389), Angenheister (51), Bauer (112), and others, the disturbance field, which is produced by the daily fluctuations prevalent in the normal magnetic earth field, is obviously caused by cyclones of electric charges or those disturbances which circulate in the highest formations of the earth's atmosphere and whose distribution is influenced by the rays of the sun. One can thus conceive with the closest approximation that the variations which take place in the course of a day, are repeated in the same manner at all places of the same geographic latitude with reference to the local time. If one always calculates according to local time, then this time applies closely for all places with the same latitude as, for instance, Potsdam. If this general rule changes regionally in detail because of various conditions, for instance, the irregular distribution of land and water, etc., one can still derive from it important data for the making of magnetic field measurements and their reduction for purposes of analysis. Except in regions very strongly disturbed locally, the variations of the local time may be taken with entirely sufficient approximation from registrations at a magnetic observatory lying in the vicinity.

The following is a list of magnetic observatories at which registrations of the elements of terrestrial magnetism are being

carried out (from the communications of De Bilt (312); *cf.* also the reports of Fleming (457) and Chree (304*a*)).

TABLE IV.—LIST OF OBSERVATORIES MAKING MAGNETIC OBSERVATIONS

λ	φ	
0° 0′	+51° 28′	Greenwich
0 30	+40 49	Tortosa
2 1	+48 49	Val-Joyeux
4 22	+50 48	Uccle
5 11	+52 6	De Bilt
7 14	+51 29	Bochum
11 37	+48 9	Munich
12 27	+55 51	Rude Skov
13 1	+52 17	Seddin
18 12	+47 53	O'Gyalla (near Budapest)
21 15	+52 7	Swider
26 39	+67 22	Sodankylä
30 29	+59 41	Pavlowsk
31 21	+29 52	Helwan
48 51	+55 50	Sajmistche (near Kasan)
56 24	+73 15	Matochkin Shar (Nowaja Semlja)
57 33	−20 6	Mauritius
60 38	+56 50	Ekaterinburg
72 49	+18 54	Bombay
78 3	+30 19	Dehra Dun
104 2	+52 28	Jouy (near Irkutsk)
106 47	− 6 35	Buitenzorg
115 53	−30 19	Watheroo
120 19	+36 4	Tsingtau
121 2	+31 19	Lukiapang
121 10	+14 36	Antipolo
140 11	+36 14	Kakioka
145 28	−37 32	Toolangi
172 37	−43 32	Christchurch
188 14	−13 48	Samoa
201 56	+21 19	Honolulu
224 40	+57 3	Sitka
246 39	+54 37	Meanook
249 10	+32 15	Tucson
280 44	+43 47	Agincourt
283 9	+38 44	Cheltenham
284 40	−12 3	Huancayo
294 33	+18 9	Porto Rico
296 9	−31 41	Pilar
316 21	−22 24	Vassouras
334 21	+37 46	San Miguel
351 35	+40 12	Coimbra
353 48	+36 28	San Fernando
356 48	+55 19	Eskdalemuir
357 32	+53 51	Stonyhurst
358 27	+47 15	Nantes (Petit-Port)
358 48	+60 9	Lerwick
359 41	+51 28	Kew

An example of another graphic representation of the daily variation is given by the vector diagram (Fig. 24) as the yearly

average for Potsdam. Here, from the zero point of a rectangular system of coordinates, the ΔX and ΔY of the vector of the daily variation in annual cross-sections for Potsdam are plotted as ordinates and abscissae of a curve. In the same way such a curve may be shown for ΔX and ΔZ. As in the above analyses, this curve applies in the closest approximation for all places of the same geographical latitude as Potsdam, if the time is considered as true local time. A similar curve can likewise be plotted for each individual month.

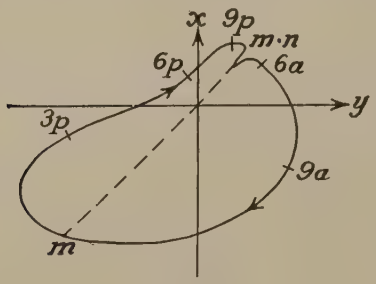

FIG. 24.

The methods by which the daily variation can be considered as the potential of a field of disturbance cannot be gone into here in detail. For this, see, for instance, Nippoldt (1148, pp. 1366–7; 1172), Schuster (1411), and Piltschikoff (1239).

Solar eclipses, according to Carlheim-Gyllensköld (288) and Nippoldt (1171), cause small changes of the magnetic field like the nocturnal course of the periodic variations.

Secular Variations.—Besides the periodic variations of direction and magnitude, mentioned above, the magnetic force of the earth field also produces very slow changes, the secular variations. Reliable series of observations do not go far enough back to be able to derive laws of periodicity in the strong fluctuations in measurements determined from year to year, and especially in variations in the annual average value of the earth's magnetic elements. The average values of D, I, H, T, X, Y, Z, in Potsdam, together with their annual variations, are given by Nippoldt (1148) and Schmidt (1390) for the years 1890 to 1921. Table V gives the values for 1922 to 1924.

TABLE V[1]

	D	I	H	T	X	Y	Z
1922	7° 7.7′	66° 35.7′	0.18576	0.46766	0.18432	−0.02305	0.42918
1923	6 56.9	66 36.5	0.18565	0.46763	0.18429	−0.02246	0.42920
1924	6 45.0	66 38.0	0.18550	0.46771	0.18422	−0.02180	0.42935

[1] According to a private communication from Professor Nippoldt.

From these compilations, the irregularity of the changes is clearly recognized. Extrapolations for coming years are therefore very uncertain. The strong fluctuations of secular variations during this period are also shown in a mathematical collection of observations made at the same or neighboring places. For the purposes of applied geophysics, the course and the physical origin of the secular variations in general may be neglected. Exhaustive treatments of the secular variations of earth magnetism are found in Bauer (110, 119), Bidlingmaier (184), Hellmann (685), Schmidt (1387), Maurain and de Madinhac (1062), Abels (3), Bartels (101*a*).

Sudden Disturbances.—These periodic and slow changes in terrestrial magnetism, according to Bauer (129), owe their origin to obviously extraterrestrial causes, and appear to be closely connected with the passage of sun spots and the changes in the intensity of the sun's luminosity due to their presence. The very considerable energy which such processes (also designated as magnetic storms) contain arises, according to Chapman (290), only in part from the sun, and it appears to radiate from limited areas; it is also derived from terrestrial sources of energy. The frequency and magnitude of the solar disturbances of the earth's magnetic field (magnetic storms), because of their connection with processes on the sun, show a period whose length, according to Angenheister (43, 46) and Cortie (318), corresponds to the period of rotation of the sun on its axis, *i.e.*, in about 27 days. Furthermore, the periodicity of the sun spots, which embraces about 11 years, is remarkable, as Cortie (318), Bauer (122, 123), Chapman (292), Evershed (441), Angenheister (48), Abbot (1*a*), and Chree (303) report. In all investigations into local earth-magnetic conditions, the observations must be freed from the influence of such disturbances. These usually appear on the whole earth at almost exactly the same moment, as reported by Lloyd (970), Angenheister (42), Bager (89). According to Bauer (116, 117), Faris (444), Fleming (457*a*), and Rodés (1296), the rate of travel in an east-west direction amounts to 100 to 200 km. per second. Bauer and Peters (133) also find disturbances which move from the equator to the pole with a velocity of some 100 km. per second (*e.g.*, Bock (194*a*), Absalom (5*a*), Mitchell (1121*a*)). The amplitude of the disturbances is in part greatest in the vicinity of the pole, while the other part reaches its maximum expression at the equator. In this connec-

tion, it is brought out by Bauer (129), Chapman (292), Birkeland (188), that the first disturbances proceed from rays (electrons or α particles) which appear in the earth's atmosphere in the vicinity of the pole, where they cause the phenomena of the southern or northern lights, which stand in close connection with the appearance of magnetic weather; while the equatorial disturbances originate through the effects of cosmic processes on a ring of electric currents surrounding the equatorial plane of the earth at great heights. The existence of these rays and also the explanation of other properties of the terrestrial magnetic field have been derived and theoretically explained by Schmidt (1389), Chapman (291, 293), Nippoldt (1148, p. 1373, *et seq.*), and others.

The disturbances as shown, for instance, by Bosler (215) usually begin with a sudden strong change of the magnetic field, followed by a slow return to normal which may require several days. The question of how far these "after-disturbances," supplementing one another, can influence the course of secular variations is discussed by van Bemmelen (157, 159) and Angenheister (49).

According to the investigations of Eschenhagen (429), Abbe (1), Ebert (377), Kohlrausch (850), and Nippoldt (1170), Pödder (1242*a*) using instruments having very short periods, the disturbances indicated on the normal registration apparatus are grouped together as elementary waves (pulsations) of very short periods up to 0.025 sec. It is customary, especially in the apparatus used for field measurements and for the purposes of applied geophysics, to designate these by their total effect. On the other hand, these fluctuations are attributed by Ebert (377), Giese (548), Andreesen (39*a*), to their induction effects on closed wire loops. By insertion of masses of iron into the wire loops or coils, according to Eschenhagen (433) and Dieterici (351), the induction effect may be intensified or the size of the coils and number of turns may be decreased. For our purpose they may still eventually attain importance, as has been shown in detail in the treatment of earth currents.

In the comparison of magnetic observations which have been made for the purpose of applied geophysics, with the corresponding values taken from registering instruments rigidly set up at stations not too far apart, one must assume as a basis simultaneous occurrence of sudden disturbances, as exemplified above,

taking into consideration the local time. If no continuously registering instrument is located sufficiently close to the region under observation, then one must erect in that region a special base station with self-registering instruments, in the manner described by Haussmann (641, 646), Eschenhagen (431), and Schering and Nippoldt (1360).

In making searches for salt domes, wherein determinations of the distribution of the vertical component of the earth's magnetism are made by means of Schmidt's field balance, notable changes in the normal value (up to 50γ) occasionally occur during stronger storms. It is not yet established whether these great changes are to be completely ascribed to the earth's field itself, or whether a change in the distribution of the magnetism has occurred in the magnet of the balance. After-effects of flashes of lightning on the earth's magnetic field have been determined at observatories.

If a strong magnetic storm has occurred during a series of measurements, care must be taken to recognize the same systematic changes of both kinds in order that they may be eliminated from the series of observations—by means of timely control measurements.

The effects of earthquakes observed accidentally, according to Eschenhagen (428*a*), Nippoldt (1177), Liznar (966), are mostly attributed to the mechanical effects due to the violent shaking of the apparatus. Bauer (109) reports on the magnetic disturbances simultaneous with the outbreak of Mont Pelée. Steiner (1477) believes that earthquakes can also bring about actual changes in the earth's magnetic field.

The Normal Space Distribution of the Magnetic Field along the Surface of the Earth.—The previous considerations make it possible to reduce each individual observed value of the elements of the earth's magnetic field, with respect to areal distribution, to a definite time, so that it can be compared with observations made at other places. The areal distribution of the mean normal comparison value of the magnetic field along the surface of the earth will now be treated, in order to proceed to the local variations of the normal areal distribution, whose study forms the problem of applied geophysics.

Observations on the magnitude and direction of the magnetic field, carried out over a period of time and at many places on land and on sea, have shown, according to Bauer (108, 110) and

Nippoldt (1177, p. 35; 1148, p. 1336), that the condition of the earth is perhaps most nearly equivalent to that which would be caused by a bar magnet in its interior, which in the year 1830 lay in a straight line cutting the surface of the earth at the magnetic North Pole, in 73° 35′ north latitude and 264° 21′ longitude east of Greenwich, and at the magnetic South Pole, in 72° 35′ south latitude and 152° 30′ longitude east of Greenwich. Because of the secular variation, these points are displaced in the course of time. The magnetic moment of this magnet for 1922 is equal to $8 \cdot 10^{25}$ c.g.s. units, *i.e.*, the earth is magnetized some 10^{-4} times as strongly as an equally large sphere of steel could be magnetized in the most extreme case, (Fleming 457*a*). The magnetic center of the earth, according to Schmidt (1390*b*), lies 300 km. from its geometric center, in direction 10° north latitude and 168° east longitude. The Gauss theory (520) of the distribution of the earth's magnetic force on the surface of the earth, which rests on a purely phenomenological basis, shows how one can derive values of the earth's magnetic field from a large number of observations taken at points regularly distributed on the surface of the earth, and measured to the same epoch. The whole field of force along the entire surface of the earth, and the potential functions belonging to this field of force, may be determined. Calculations of the coefficients of the potentials of the earth's magnetic field, and expressed as functions of spherical coordinates, are found in Schmidt (1375), Bauer (126), and others. On the physical sources of this magnetization, see Gauss' complete theory. In developing his theory, Gauss neglects all local influences and is content throughout with establishing the average regional value.

For our particular purpose, we do not need to consider further the physical origin of the magnetization of the earth as a whole (see, for instance, Nippoldt (1177, p. 50 *et seq.;* 1177*a*)). According to Bauer (126), Fleming (457*a*) and Angenheister (51), one can assume the theory that 94 per cent of the earth's field originates in the interior of the earth; 3 per cent is determined by an exterior field; the remaining 3 per cent possesses no definite origin. Further reference may be made to several publications of Naumann (1153), Belot (156), Bauer (118, 129), Bartels (101*b*), Hazard (654*b*), Swann (1504*a*), Schmidt (1389). We are, however, interested directly in the local deviations from this general magnetization on account of geologic heterogeneities

in the crust of the earth, and only from this point of view shall we discuss the distribution of the magnetic field as a whole.

Because of the deviation of the magnetic axis from the axis of rotation of the earth, and because of the effect of additional fields on this main general magnetization of the earth, the planes which are perpendicular to the surface of the earth, and parallel to the direction of the compass needle, do not coincide with the geographic meridians. However, if one connects successively all points of similar declination on the surface of the earth, then one obtains a system of isogons, lines of similar declination, which run together at four points on the surface of the earth, at the magnetic and at the torsional poles of the earth (at the latter points only on purely geometrical grounds). For the same reason, the lines of similar inclination (isoclines), the lines of similar total intensity (total isodynamics), lines of similar horizontal intensity (horizontal isodynamics) and the lines of similar vertical intensity (vertical isodynamics) do not coincide with the circles of latitude, but in many regions deviate very notably from this direction.

In the last two decades, the general magnetic measurement of the entire earth has made extraordinary progress through the work of the terrestrial magnetic division of the Carnegie Institution in Washington under Bauer's direction. The voyages of the yachts *Galileo* and *Carnegie*, which are free from iron, on which among others Bauer (121, 115, 126*a*), Fleming (457*a*), Ault (72, 73), Nippoldt (1179) have reported, have not only determined the distribution of magnetic force on the seas by a close network of observation points, but also, according to Bauer and Fleming (131), Chree (304*a*), and others, have afforded valuable material for the most exact coordination of the instruments which are used in the magnetic observatories in different countries. The results are set down in the *Researches of the Department of Terrestrial Magnetism, Carnegie Institution, Washington* (1028). The measurement ship *Cecilie* has been recently equipped by Germany and Esthonia; its equipment and program have been described by von Gernet (533).

The curves of equal value of the magnetic elements, drawn on the basis of Gauss' theory from a valuation of all the observation materials on the whole earth, are designated as terrestrial isomagnetic lines. These take no account of local disturbances, except in so far as the latter affect the measured values at points

taken as the bases of these calculations; through careful selection of these points, however, it is sought to keep the observation material free from the influence of local disturbances.

Instead of drawing these isomagnetic lines themselves, Lamont (900) proposes to connect all places having equal space variations (gradients) of the earth magnetic elements with one another and with a main station (for instance, Munich) by relative isomagnetic lines. He hopes to avoid thereby the variability of the line picture through secular variation. Since, however, the latter can be spatially different in any case, this representation has been used for land measurements and has often proved extremely appropriate for local disturbances.

An exposition of the general formula from Gauss' theory of earth magnetism, for the distribution of the earth magnetic force along the entire surface of the earth, must naturally be disregarded here. For the distribution of terrestrial isomagnetic elements within Germany, as well as for its related secular variations, Schmidt (1376) and Nippoldt (1177, p. 59) give simple formulæ which are developed according to geographic longitude and latitude. Corresponding formulæ for the terrestrial total isodynamics for France are published by Mathias (1051).

The change of magnetic force with height above sea level, according to the theory, is only very slight. It is, therefore, for our purpose practically without importance. Attempts have been made to measure this change through observations on mountains, in mines or in balloons without, however, obtaining entirely satisfactory results, because of the smallness of the effect (see the investigations of Koristka (860), Hoppe (740), Meyer (1098), Messerschmidt (1091), Liznar (962, 967), Schmidt (1377), Brunhes and David (260), Mathias (1051*a*), Brückmann (254), Pochettino (1240), Senouque (1430*a*), Hazard (654*a*), Penkevitch (1219*a*), and others). Bauer (130*a*) gives some theoretical references to this question. According to Schmidt (1377), the time variations of the magnetic force in a mine have been found to coincide with those on the surface of the earth. In regions of disturbance, this conformity may not occur (see Passalskij 951, 1212, 1213).

A map showing the isomagnetic lines of the earth will not be shown here, since the scale of the map would be so small that it could not be used for the purpose of applied geophysics. A comprehensive collection of a great number of magnetic land measure-

ments also must unfortunately be omitted for want of space. Only the most recent magnetic measurements and magnetic maps of some especially important countries and some comprehensive reports on magnetic land measurements, in general, will be mentioned.

The results of the more recent land measurements are given: for instance, by Nippoldt (1175, for 1909.0), Haussmann (646, for 1912.0; 648, for 1921.5; 649, for 1925.5), Lüdemann (987*a*) for Germany; Schering and Nippoldt (1360, for 1923.0) for Hesse; Burmeister (274*a*) for Bavaria; Moureaux (1141, for 1896.0), terrestrial and true isomagnetic lines are given by de Madinhac and Homery (1024*a*) for France; Angot (52, for 1901.0) likewise for France; Rücker and Torpe (1313, for 1891.0) for Great Britain; Schedler (1353, for 1918) for Austria; Hermant (713*a*) for Belgium; de Martonne (1047*a* for 1926) for North Africa; Rose (1299*a* for 1925) for Russia; Hazard (653) for the United States of America. Comprehensive reports on later and most recent earth-magnetic measurements are given by Nippoldt (1173, 1179) and Ault (72). The older earth-magnetic work has been clearly compiled by Hellmann (685) in his magnetic cartography.

The terrestrial isomagnetic lines differ considerably from the true isomagnetic lines, by reason of the fact that the values of the magnetic elements in question, measured in as narrow a network of observation stations as possible, are directly interpolated, as for instance, by Moureaux (1141). While the terrestrial lines in their determination show a flatly curved symmetrical course over wide areas, the guide lines of the true isomagnetic curves, as is shown in the isogon map of Haussmann (649), generally become the more complicated as the observation points are taken at closer intervals, since the spatial distribution of the disturbances is more completely worked out.

The new maps of the German Empire, by Schmidt (1379, 1381), Nippoldt (1175), have adopted a well-thought-out middle course between the representations by means of terrestrial and true isomagnetic lines. While the lines have been drawn in adjusted form in accordance with the mean values of the observation points, assembled in groups at each place of observation, the difference of the true measured value from that of the curve also has been interpolated.

The difference between the terrestrial and the true magnetic magnitude is designated as a local "anomaly." Its course can

be shown by isanomalies of the elements concerned (for instance vertical intensity), while all points with equal differences between the terrestrial and true values of the given magnitudes are connected by curved lines. However, in many practical cases, one can advantageously calculate or construct the vectorial differences of the terrestrial and the true earth-magnetic force vectors as "local disturbance vectors," since in them the disturbances extending over more or less great areas are more completely worked out. These disturbance vectors can be designated on a map, as proposed by Ambronn (412), by arrows to scale according to direction and magnitude; or the values corresponding to the places of observation can be brought out in relief; only the horizontal components of the disturbance vectors may be brought in as arrows to scale on the map with the vertical components within numerically or otherwise designated, or as done by Eschenhagen (430) (reproduced by Nippoldt, 1148, p. 1347), they may be shown regionally by lines of similar vertical disturbance and shaded surfaces (see Fig. 34). Likewise, one can often profitably project the disturbance vector on a vertical plane, for instance the plane of the magnetic meridian, as is brought out in Fig. 37. This representation often gives an immediate idea of the depth of the disturbing body. Carlheim-Gyllensköld (285, 286) draws the level lines of the disturbance potential on the map, so that one can make independent deductions from this representation of the disturbance vectors. Reference may also be made here to the explanation of Piltschikoff (1239).

As examples of areally extensive disturbances, the continents themselves are notable, according to Bauer (114), who calls them continental disturbances. Rücker (1311*a*) and Raclot 1268*a*) consider the oceans as regions more strongly magnetized than the continents. Also islands in the ocean, especially those of volcanic origin, according to Creak (321, 322), Cirera (306), Paulsen (1214), Farr (445), Fisk (454), Palazzo (1208*a*), effect changes in the normal distribution of the earth's magnetic field. Neither phenomenon, however, falls within the scope of our consideration. Our patterns of the disturbances extending over greater regions are nearer at hand, as they are due according to Kreil (870), Meyer (1098), Naumann (1153), Eschenhagen (430), to extensive mountain chains (Alps, Apennines, Harz, etc.) and to their general geologic-tectonic structure.

It is important for our special task, however, first to treat of the characteristics of local magnetic disturbance regions limited to smaller regions. These will be treated through the character of the special geologic structure of the subsoil, especially through the deposition of economically valuable formations, to which later detailed consideration will be given.

Instruments for Measuring the Earth's Magnetic Elements.—Considering the length of time in which terrestrial magnetic measurements have been carried out, the number of kinds of apparatus constructed is very great; so that we will have to be content here with a brief survey of the more important published literature. The annual reports of the different magnetic observatories contain mostly data on the construction and erection of the present station apparatus, including current reports on the experience gained by them and the improvements made in them (*cf.*, for instance, (1028)). Since it is impossible to give this comprehensive literature here, reference must be made to the list of regularly registering stations on page 65, Table IV. Nippoldt (1178), for instance, is occupied with the historical development of earth-magnetic instruments.

One can next (although from related grounds this classification is not obvious) differentiate between instruments and methods for absolute and those for relative determination of the different elements of the earth-magnetic field. In more recent times for the work of applied geophysics, instruments and methods for relative determinations have been preferred, hence these will receive most consideration.

Another classification of magnetic measurement methods (see Bauer (120)) depends on the physical properties of the earth's magnetic field, since this exerts an attractive force on bar magnets or on direct-current coils which are readily transported. The earth-magnetic field produces a magnetizing effect on soft iron, and also will excite electromotive forces in a coil of wire when it is rotated about a diameter in the earth's field. Von Eötvös (396, 397) has tried to make practical use of a further property of the heterogeneous terrestrial field, namely, that of exerting on bar magnets a translatory force proportioned to the degree of its heterogeneity; technical difficulties appear, however, because of the smallness of the force on the magnet; on the other hand, the forces exerted individually on the two poles of the bar are so great that this method of measuring the gradients of

magnetic force has been almost universally proposed. The striae recorded in Fig. 15 correspond to the length and direction of gradients obtained by this method. A proposal to determine the gradients of the magnetic field by induction effects was made by Ambronn (414), but this has not yet been practically carried out. Another method indicated by Rawen (1274) involves either the application of an ordinary Weber earth inductor or dispense with physical methods in general.

Next will be considered the movement of a bar magnet with horizontal magnetic axis, around a vertical axis. The axis of rotation can be either a thin wire, or, according to Chapman and Bryant (294), a filament of a single tungsten crystal from which the magnet is suspended; or the magnet may be supported on a pin. In order to counteract the tilting effect of the vertical component of terrestrial magnetism, one side of the needle is weighted. The needle, thus free to move in a horizontal plane, sets itself with the line joining its poles, *i.e.* its magnetic axis in the magnetic meridian. In order to establish the direction of the magnetic axis in the bar as sharply and invariably as possible, it is given the form of an elongated horizontal rhombus or a thin lamella whose surface stands perpendicular. The torsional moment due to any twisting of the suspending filament, and of the friction in the pin, must be taken into consideration. The reading is obtained either immediately at the point of the needle, which is suspended over a scale, or by means of a telescope and a scale which is reflected in a mirror rigidly connected with the rod, according to Poggendorff's well-known method. Probable asymmetry of the system is eliminated by inclination of the bar (interchange from above and below), as well as also by demagnetization. On this basis is constructed the simple compass, as well as the contrivance of the magnetic theodolite for determining the earth-magnetic declination according to Lamont (898), Fleming (456), Wild (1625), Haussmann (644), Liznar (964), Venske (1561), and others. In ship's compasses, however, it is customary to connect the scale, or rosette, with the movable magnet system, and to read its position relative to fixed marks. In order to diminish the notable pressure of the movable parts on the pin, the compass is enclosed in a chamber and the movable magnet system is allowed to float in an alcohol-water mixture (fluid compass).

The magnetic declination is determined by comparison of the direction of the magnetic force with the direction of astronomic meridian. On the magnetic theodolite used for exact measurements of declination, the telescope, which is adjusted by observation of the position of the mirror fastened to the magnet, is so directed that one can adjust the azimuth at will from a terrestrial or astronomical reference point on a graduated circle. Figure 25 shows such a magnetic theodolite with all its appurtenances in modern form. A mechanical self-registering declinatorium has been described, for example by Cady (282). Usually this registration in magnetic measuring instruments is done photographically.

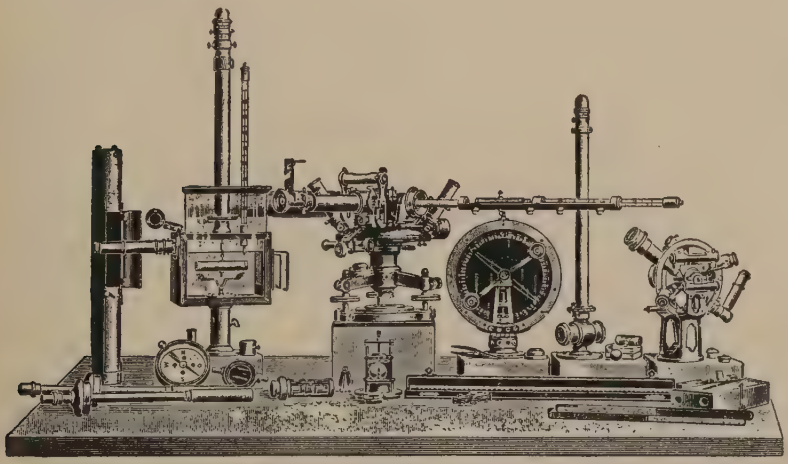

FIG. 25.—(After Eschenhagen.)

A very simple contrivance for determining the magnetic declination, which has been used especially in America, for instance by Hotchkiss (743) and Smyth (1459), for quick exploration of large districts, consists of the connection of a sundial with the compass needle (dial-compass). In the dial-compass, the sundial serves to regulate the average sun time shown by an exact clock by comparison of the midday line of the sundial scale in the astronomical meridian. The deviation of a compass needle rigidly connected to the same plate as the sundial is read from the true north-south direction on this scale.

The magnetic moment M of a bar magnet is equal to its polar strength multiplied by its distance between its poles. If one

lets a bar magnet of polar strength M, which rotates freely about a vertical axis, swing to its position of rest, then its period of oscillation is

$$\tau = \sqrt{\frac{\pi^2 \cdot K}{M \cdot H}},$$

where H indicates the horizontal intensity of the earth magnetism at the place of measurement, and K the moment of inertia of the bar magnet about its torsion axis. τ is easy to observe, K can be calculated from the dimensions of the bar according to known formulae, $\pi = 3.14159 \ldots$ One can also calculate $M \cdot H$. If observations are taken simultaneously with similar magnets at places with different values of horizontal intensity, then the horizontal intensities at the different places are the reciprocal of the squares of their periods of oscillation (finally reduced to

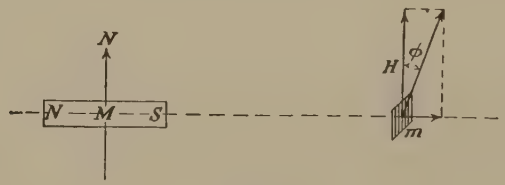

FIG. 26.

oscillations of small extent). From this, the assumption is made that M will remain sufficiently constant (or that its changes with temperature, etc., will be considered), which with suitable handling of the magnets, according to Leyst (949), Andrade (38), Schmidt (1382), Liznar (965), and others, is very accurately possible.

In order to separate M and H from each other, the magnetic field derived from the magnet with the magnetic moment M is compared with the earth's field H, while both are allowed to act simultaneously on a small magnetic needle which turns freely about a vertical axis. The comparison can result in very different ways according to the arrangement of the deflection magnet M opposite the rotating needle m and the earth field H. As an example (Fig. 26), the simple arrangement of Gauss' first main position is selected here. The deflecting magnet M lies (magnetically) east-west, and the deflected needle m lies at the distance L on the prolongation of its magnetic axis. If L is large with respect to the length of the deflection magnet, and φ is

the angle about which the magnet M deflects the small needle m from the north-south direction, then in the nearest approximation $M/H = \frac{1}{2}L^3 \cdot$ tangent φ. From $M \cdot H$ and M/H one can calculate the absolute values of M and H separately. For the many corrections in the final magnetic measurements for the elimination of temperature influences, the torsion of suspension, the reciprocal magnetic induction of the bar magnet, etc., reference must be made to the literature, for example, to Lamont (898, p. 21 *et seq.*), or Wild (1624), Leyst (949, 952), Mielberg (1104), Schmidt (1396*a*).

In the second Gauss main position, the deflecting magnet M lies north or south of the deflector magnet m, while M, furthermore, stands perpendicular to the meridian. In the third main position, M is arranged perpendicularly above or below the needle m; the magnetic axis of M lies at an angle of usually some 25° or 30° from the magnetic meridian, and the distance between the two magnets is so arranged that m is turned approximately 90° from the meridian. The Kohlrausch single-bar variometer (848, 849) uses this arrangement and is especially well suited, sensitive, and convenient for determining the local variations of horizontal intensity in the field.

It is self-evident that, in place of one deflecting magnet, several (2 or 4) can be used, arranged in different main positions, as described by Kohlrausch (846, 848, 849), Wind (1637), Poppendieck (1249), Schuster (1413). To use several needles in a common magnet field, as Brammer (233*a*) suggests, is of no advantage, because of the increased complication of the instrument. In spite of the fact that the needle of Brammer's instrument is considered especially light, an opposite magnetic influence is to be feared from it.

Another method is used, according to Lamont, mostly with the magnetic theodolite which is represented graphically in Fig. 27. The magnet m to be deflected, is suspended in the center of a graduated circle K. Its position is read in the telescope F, and the image of the illuminated cross-hairs, as reflected into the telescope from the polished magnet, is made to coincide with these (cross-hairs) themselves (Gauss' ocular). Perpendicular to the line of vision of the telescope are two bars S_1 and S_2, which are rigidly connected with the telescope, and which can be rotated with respect to the circle before mentioned. At a distance L, the deflecting magnet M will be securely fastened

upon one of the two bars. The magnet m will be deflected. The telescope, together with the bars and the magnet case, is turned through the angle φ which is read on the circle K, until the magnet m has again assumed its original position in the telescope. If k indicates the "deflection function" dependent upon the dimensions of the magnet (*cf.* Schmidt (1380*a*)), then

$$H = \frac{\pi}{t} \cdot \sqrt{\frac{2Kk}{L^3}} \sin \varphi,$$

where t will indicate the period of vibration of the magnet M, and K its moment of inertia (see page 78). For particulars of this process, designated as the *sine method*, compare Lamont (898, p. 22; 899), Liznar (968), Nippoldt (1148, p. 1313 *et seq.*).

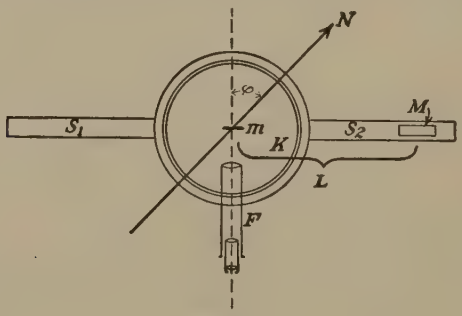

FIG. 27.

Temperature changes must be corrected for or nullified by the use of compensated deflecting magnets, according to Lamont (897) and Mascart (1049).

In all these different arrangements, the permanent magnet can be replaced by coils through which a measured electric current flows, as has been done in practice by Jenkins (763), Tanakadate (1515), Schuster (1413), Barnett (98), Smith (1456), LaCour (888*a*), Fleming (457*a*), Uljanin (1555*b*).

Finally, the torsion moment exerted by the earth's field on the magnet movable about a vertical axis can be counteracted by mechanical force. As the magnet, according to Kohlrausch (847), is suspended by one or two threads, it can be turned by the torsional force of this suspension until its axis stands perpendicular to the magnetic meridian. This kind of measurement is particularly suited for variation observations. The methods previously described can be combined, as has been done by

Liznar (963), Schmidt (1380, 1386), so that the adjustment will be independent of temperature and so that one scale division assumes a given value (the sensitivity). The effect of temperature changes on the strength of the magnet bar must be taken into account (Venske (1560)), as in all magnetic measurements.

A design which is valuable on the sea and for airships is represented by Bidlingsmaier's double compass (184), in which two compass needles, freely movable about a vertical axis, are placed exactly perpendicular to each other and at such a distance from each other that they deviate 30° from the north-south direction, because of the repulsion of like poles. This instrument, according to Luyken (1009), is well suited also for the determination of local anomalies of the horizontal intensity.

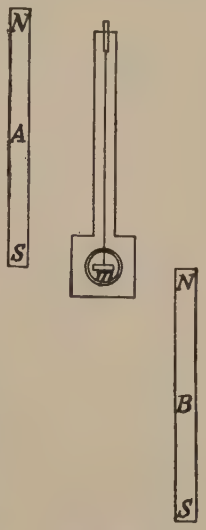

FIG. 28.

The vertical intensity can be determined, according to Lloyd (971), Nippoldt (1148, p. 1321), also by means of a horizontally swinging needle m, if one arranges, as shown in Fig. 28, two bars, A and B, of soft iron, one above and one below the plane of oscillation of the needle. These bars are magnetized inductively by the vertical component of the earth field parallel to their axes and proportional to its strength. The compass needle m suspended in the central box is then acted upon by the horizontal force of the earth's magnetic field, and by forces which originate in the two soft-iron bars and are proportional to the vertical intensity z of the earth field. In the position of equilibrium, $2kZ = H \sin \varphi$, where k indicates the instrument coefficient, and φ the angle of deflection of the magnetometer needle in equilibrium. H is known, so Z can be calculated. On the other hand, $Z/H = \sin \varphi/2k = \tan J$, so that the angle of dip J can also be determined in this manner. Since k varies fairly strongly with time, this method is recommended only for limited use in practice. Further data on this are found in Lloyd (973), Lamont (898), Schering (1357, 1358), Bücky (268), Göllnitz (570), Venske (1559). With use of this great coercive force, the induction effect of the earth field on a nickel rod is utilized in a contrivance of Williams (1629).

Lloyd employs an entirely different method in his magnetic vertical balance, in which, among others, Eschenhagen (432) and Schering (1359) follow him. Schmidt (1383) (see also Heiland (674)) has made this instrument especially suitable for field measurements. A balance beam, usually in the form of one or several parallel rhombuses, elongated and of magnetized material, is supported on both sides by a horizontal knife-edge which intersects the beam just above its center of gravity. If the knife-edge is placed in the direction of the magnetic meridian, the magnetic axis of the bar magnet being thus perpendicular to it, then the beam is only affected by the vertical force Z, which tends to turn it perpendicular to its magnetic axis. Through a small mechanical asymmetry of the beam, however, the magnetic torsion

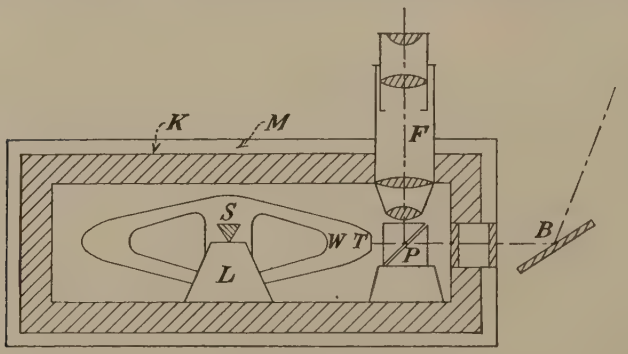

Fig. 29.

moment is so far compensated that the beam stands almost horizontal with an average value of the vertical intensity. With variations of the vertical intensity the beam then changes its inclination. The position of equilibrium is read, according to Schmidt (1383) and Heiland (678), with a mirror and telescope by autocollimation, or, according to Ambronn (33), on a scale arranged at the end of the balance beam by microscope and ocular micrometer. It can also be recorded photographically.

Figure 29 shows a sketch, after Ambronn (33), of the field balance as built for the purposes of applied geophysics, in which special precautions are taken to protect it from heat and equalize the temperature in the interior of the balance by use of the copper mantle K.

This is still further protected against heating due to radiation, by a polished casket. The magnetized balance beam W rests,

by means of the knife-edge S, on the quartz bearing L. The light is thrown from mirror B through a window upon the finely divided scale T fastened on the balance beam, which (the scale) is observed in the prism P by means ot the telescope F, while the scale on the balance beam is still further subdivided optically by an ocular micrometer.

A magnetic balance with crossed magnet bars, whose properties have been investigated by Toepler (1543*a*; 1386, p. 309), was proposed by Haalck (616), who believed advantage was gained thereby. However, the magnet cross is mechanically and magnetically equivalent to a simple magnet bar placed obliquely; so that this construction has no advantage, but is detrimental because of the complicated influence of the temperature on the two bar magnets. The method of compensating the influence of the horizontal intensity against the vertical intensity by turning the axis of the balance beam in azimuth must be considered, since unstable positions become possible.

A disadvantage of this instrument is the asymmetry between the mass of the balance beam and the magnetic moment practically bestowable on it. The pressure of the knife-edge must be assumed as very great, and the torsion moment, caused by variations, in practice is still only very slight. The choice of the right knife-edge material has already required much experimentation, without complete success as yet, although agate, quartz, or chrome steel knife-edges seem to be preferred. The volomite used as a substitute for diamonds in drilling, proposed by Ambronn (406), unfortunately has not proved practical so far on other grounds. Various attempts have been made to replace the knife-edges by quartz or similar filaments; according to Watson (1584), Venske (1558), no results have been obtained in this direction, but Koenigsberger (838) and Angenheister (51*b*) believe more favorable results have been attained in this direction. Andreesen (39*a*) let the magnets float in glycerine, to lessen the load on the filaments.

Apart from the methods described above, the inclination is measured by means of a needle swinging in the plane of the magnetic meridian and about a horizontal axis. The center of gravity of the needle corresponds as precisely as possible with its torsional axis. The mechanical balancing of the needle, and the overcoming of the axial friction offer great difficulties in the construction of the device. The theory of the dip needle,

as it is generally called, cannot be gone into here. It has been treated by Leyst (948), Rikatscheff (1295), and others. The models of Nippoldt (1148, p. 1303 *et seq.*) also should be referred to. On a special form of dip needle with inclined axis there is a report by Gruber (585).

If one does not balance the mechanical forces about the axis of rotation completely, but (as in the precision instrument in Lloyd's balance) allows the magnetic torsion moment of the needle to be balanced by an equal mechanical torsion moment, the needle itself, however, swinging about an east-west axis in the magnetic meridian, then one obtains the dip-needle often employed in Sweden and North America for rough measurements.

Because of the collective effects of variations of inclination and the intensity of the earth field, the theory of this instrument is rather complex, especially if use is also made of the deflection magnet. If, as is the rule, it is used only for estimate measurements, then, because of its simplicity, it renders good service in investigations of regions of large magnetic disturbances, for instance, those produced by deposits of iron ore. More detailed data on the construction, use, and explanation of this instrument are found in Fox (478), Fox and Jordan (483), Lloyd (969), Tiberg (1538), Dahlblom (326), Uhlich (1555), Hotchkiss (743), Smyth (1459).

An entirely different physical property of the magnetic field from those used in the methods already treated, is used in the measurements with the Weber earth inductor (520, pp. 86–101; 1590, p. 81 *et seq.*). Compare also the models of Nippoldt (1148, p. 762 *et seq.* and p. 1305 *et seq.*), Venske (1557), Dorsey (356). Ault (73*a*) recommends the use of the induction principle in investigations into the structure of the earth's magnetic field at great heights by means of registering instruments carried aloft by balloons. The earth inductor is based on the knowledge that if a wire coil is moved in a magnetic field, an electromotive force is set up which is proportional to the number of lines of force cutting the coil per second. If the resistance of the coil and its associated circuit, including the galvanometer used in the measurements, is known, then the quantity of electricity caused to flow in moving the coil from a given initial position to a given end position (as far as the magnetic field within the region investigated has a potential) is independent of the path and only proportional to the difference of the number of lines of magnetic

force cutting the coil in the two bounding positions. Lines of force cutting the coil in opposite directions give opposite signs to the readings. If one turns, for instance, a plane coil through exactly 180°, so that only the direction of the lines of force cutting it are reversed, then the quantity of electricity excited thereby is proportional to the field strength perpendicular to the plane of the coil. The amount of electricity can be measured by a ballistic galvanometer. If H is the field strength of the component of the magnetic field perpendicular to the coil, W the resistance of the coil and the closed (measuring) circuit, F the area enclosed by the wire coil (with coils of n turns which individually enclose the surface f, $F = n \cdot f$), then the amount of electricity excited, according to Nippoldt (1148, p. 761 *et seq.*), will be $Q = 2 \cdot F \cdot H/W$, while with a change of the field strength from the value H_1 to H_2 a quantity of electricity $Q = F \cdot (H_2 - H_1)/W$ will be induced.

Besides the determination of absolute field strengths, and differences of field strength, the practical uses of this method (Haalck (615)) are manifold. For instance, if, in a uniform field, one turns the coil about an axis parallel to the lines of force, no current is set up, since the lines of force remain parallel to the plane of the coil, and there is no component perpendicular to the plane of the coil. If, now, a direct-current galvanometer is connected across the coil through a commutator which rectifies the alternating current set up by the rotation of the coil in the earth's field, and if the axis of rotation of the coil is turned round in space, then no current passes through the galvanometer when the axis of rotation is parallel to the lines of magnetic force. The inclination of this axis of rotation to the horizontal gives the angle of dip. These processes, according to Nippoldt (1148, p. 1305 *et seq.*), Dorsey (356), Venske (1557), Bauer (1028, Vol. II), seem the most exact methods for this determination at present. Figure 30 gives an illustration of an instrument of this kind from Potsdam, which is used extensively.

Another method for determining the dip by means of the earth inductor, according to Weber (1587), is to measure the horizontal and the vertical intensities only by rotating the coil through 180°. The ratio of these two values gives the tangent of the angle of dip. Thus it is not necessary even to know the constants of the apparatus.

In very delicate, especially differential, measurements, disturbances can originate from thermal electromotive forces acting in the circuit, particularly at the commutator segments, by contact resistance produced by dirt, and by electrochemically excited electromotive forces. Ambronn has, therefore, proposed to enclose the rotating coil, and to induce a current in an adjacent stationary coil by means of the current flowing in the enclosed rotating coil. Stumpf also suggests concentric coaxial coils lying within one another, one of which is rotated, while the other is connected to the measuring instrument. Finally, these

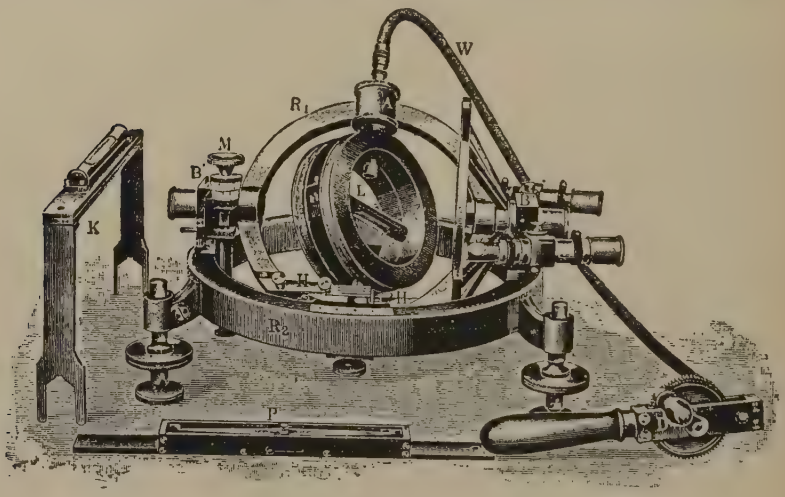

FIG. 30.

methods of field measurement by means of rotating coils, according to Perot (1221), Watanabe and Kawamura (1581), Shaxby (1438), Ambronn (33), can be used as "null" methods, by compensating for the earth's field in the neighborhood of the rotating coil by impressing measurable electromotive forces on the coil system.

An important source of errors, especially in magnetic field measurements, lies in the irregular performance of the apparatus used in the measurements. This is due in part to mechanical changes, and in part to magnetic changes in the measuring instrument. The most careful treatment and exact adjustment of the instrument, as well as an observation program which links the series of observations systematically with one point

of reference, and so prevents the appearance of any intermediate changes in the instrument, is therefore absolutely necessary.

In absolute measurements of all components, the greatest possible variation of the instruments in the course of a complete set of observations must be taken into account, and it is necessary, therefore, as a last precaution to check periodically on the main terrestrial magnetic stations. In the instruments which are used almost exclusively today in magnetic field measurements, for the purposes of geophysical investigation for only relative measurements, one must eliminate changes in the apparatus, by suitable linking of the series of measurements.

The Applicability of Magnetic Methods for the Work of Geophysical Prospecting.—In using magnetic methods for the study of the geologic structure of the uppermost formations of the crust of the earth, the question arises as to whether the local anomalies in the distribution of the magnetic forces have been brought about by the deposition of magnetic or magnetizable masses, or by the magnetic field of earth currents. In the first case, the magnetic measurements allow conclusions concerning the subsurface form of the hidden mass of magnetic or magnetizable rock; in the latter case, data are collected concerning the subsurface distribution of the electric conductivity. While in earlier times opinion was divided on this question, and Naumann (1153, 1154), for instance, believed the latter idea to be proved, the general tendency now is toward the view that earth currents usually do not come into consideration in the production of magnetic anomalies. In many cases, for instance by Rücker (1309), Paulsen (1214), Passalskij (1213), Carlheim-Gyllensköld (287, 289), Lasareff (910), proof could even be obtained that well-defined magnetic anomalies correspond in form and size to the circumference and the magnetic properties of magnetizable masses underground. These masses were checked geologically.

According to Lasareff (916), the magnetic field of magnetizable masses, in contrast to an electromagnetic field excited by electric currents in the earth, on theoretical grounds must also exhibit essential differences in its areal pattern, and in this way might be differentiated. The application of this principle to a particular case has not been recognized thus far. The phenomena in the crust of the earth usually designated as "earth currents," are due to the most varied causes, as Barus, for instance (102, p.

365), has emphasized. They do not come into consideration in the excitation of permanent local phenomena.

The gravity disturbances, often paralleling the magnetic anomalies, afford further proof of this fact, as the strongly magnetizable eruptive and intrusive rocks with their high content of magnetite also form centers of gravity disturbances and indicate regions of excess gravity. Tanakadate (1515), von Eötvös (396, 397), Eschenhagen (430), Riccó (1292), Colin (310), Deecke (339), Bahn (90), Lasareff (914), Lagrange (889), Hazard (654), show many examples of this close connection. On the other hand, the converse phenomenon is found, for instance, in salt domes, where regions of minimum vertical magnetic force coincide with the smallest effects of gravity, as the works of Schweydar (1421), Nippoldt (1176), Schuh (1402), Haalck and Brinckmeier (617), Koenigsberger (837), and Ambronn (33) show.

The Magnetic Properties of Rocks and Their Measurements.— As a basis for the further study of the connection of local magnetic anomalies with the geologic structure of the uppermost formations of the earth, we must first consider the properties of the rocks composing these formations and discuss the means of determining these properties from samples.

The magnetization of rock or mineral masses in the subsoil results from induction in the earth field. The magnetization of a piece of iron in this way may be treated first as an example.

Between the elongated and parallel polar planes N and S of a magnet (Fig. 31), a homogeneous magnetic field exists, which may be indicated by the fine parallel lines. If a piece of soft iron is brought into this field, it causes lines of force to crowd together, as the heavy lines in Fig. 31 show. Iron possesses a greater susceptibility for the magnetic flux than air. Bodies in the form of an ellipsoid, as in Fig. 31, become so magnetized in a uniform field that a uniform magnetic field again arises in their interior. However, the relation can also be conceived in this way: that the iron body itself becomes a magnet through induction. This magnet builds up about itself a field of lines of force (heavy) which, overlying the uniform field, yields the strongly marked lines of force actually observed as resultants. This conception is often of great advantage in the explanation of practical data. Detailed expositions on induction are found in Müller-Pouillet (1148, p. 91), Würschmidt (1652*a*), also in

Hotchkiss (743, p. 97), from which Fig. 32 is taken, illustrating in a similar manner the magnetizing of an iron-ore vein by induction.

The measure of the magnetic conductivity of a body in contrast to a vacuum as unity, is called its *permeability* μ. In theoretical calculations the *susceptibility* $\varkappa$ is also frequently

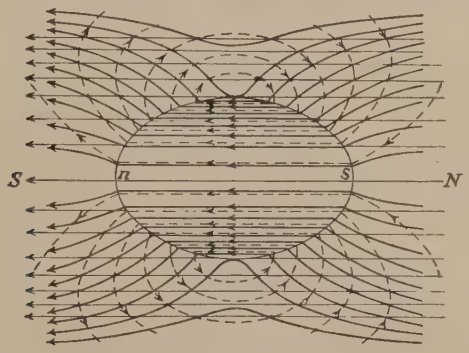

FIG. 31.

used. It is connected with μ by the relation $\mu = 1 + 4\pi\varkappa$. The complicated dependence of the permeability of ferromagnetic materials on the strength of the magnetic field is not treated here, especially as iron is practically absent from the crust of the earth. With rising temperature it generally increases, up to a

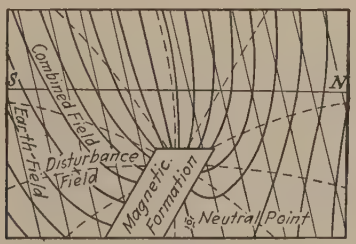

FIG. 32.

certain temperature, for iron about 780°. Above this temperature it quickly returns to 1.

Aside from the magnetizability itself, the different kinds of iron, depending upon the mechanical and thermal treatment, show the property of retaining magnetization in more or less high degree. Permanent magnets are made from materials which

show this property of "residual magnetism" in very high degree.

In addition to iron itself, strong magnetic, also called "ferromagnetic," properties are exhibited by numerous iron alloys, nickel, cobalt, and many manganese and chromium alloys; and also, according to Voigt (1569), Eriksson (422), Du Bois (200), Kunz (878), Quittner (1268), Weiss (1596), Abt (6), Smith (1457), Wilson and Herroun (1635), by some iron compounds such as magnetite, pyrrhotite, nickeliferous pyrrhotite, hematite, etc. Blanc (191*a*) has investigated a magnetic chromic oxide.

In contrast to these ferromagnetic materials, the permeability of all other materials changes within only the narrowest limits. If the permeability of a vacuum is assumed as equal to 1, then that of a ferromagnetic body lies between several hundred and 1,000; on the other hand, for all other materials it differs from unity by only several millionths. Those materials which conduct the flow of magnetic force better than a vacuum are designated as paramagnetic, and those which conduct it less well than empty space as diamagnetic. Table VI gives the susceptibilities for several elements.

TABLE VI.—SUSCEPTIBILITIES $\varkappa$ OF SEVERAL ELEMENTS

	$\varkappa$		$\varkappa$
1. Aluminum	$+ 1.8 \cdot 10^{-6}$	6. Lead	$- 1.2 \cdot 10^{-6}$
2. Bismuth	$-15 \cdot 10^{-6}$	7. Mercury	$+ 2.1 \cdot 10^{-6}$
3. Copper	$- 0.8 \cdot 10^{-6}$	8. Platinum	$+29 \cdot 10^{-6}$
4. Gold	$- 3 \cdot 10^{-6}$	9. Silver	$- 1.5 \cdot 10^{-6}$
5. Graphite	$- 8 \cdot 10^{-6}$	10. Sulphur	$- 0.8 \cdot 10^{-6}$

Rocks are generally mixtures of numerous mineral components. Their magnetic properties depend, therefore, upon those of their individual constituents, and upon percentage relations of the latter. Since ferromagnetic materials occupy such an exceptional position in respect to all other materials, and besides the different iron compounds, form such a great fraction of the rocks composing the earth, their mixture in the individual rocks, as the investigations of Frivold (490), Stutzer, Gross and Bornemann (1496) have shown, must influence in a high degree their relations to the earth's magnetic field. The origin and deposition of the different formations with respect to their iron content often changes markedly in quantity and chemical composition

from place to place, so that various specimens taken close to one another exhibit very different composition, and therefore can differ strongly in their magnetic properties.

Generally, therefore, those rocks which contain magnetic iron compounds in notable degree can be distinguished from those which lack these compounds. The former show very great differences between specimens, in the latter the para- and diamagnetic properties of the basic substance itself come more clearly to expression, and these therefore act more uniformly in greater masses in the earth's magnetic field. To the first group belong the eruptive rocks and those rocks which, through redeposition, folding, tectonics, or because of heating from neighboring magmatic masses, have suffered changes whereby the iron compounds contained in them have been precipitated in lower degrees of oxydation, or have been changed into such later. Unaltered, especially organic, sediments generally belong to the practically magnetite-free rocks.

For the quantitative or comparative determination of the magnetic permeability, numerous methods have been given. On account of the necessity of treating rocks as mixtures of great numbers of different substances, in order to obtain a good mean value, a considerable part of the methods formerly used for pure materials is eliminated. It is sufficient, therefore, to mention briefly only the characteristic ones, and, finally, to refer to the textbook on the subject, Müller-Pouillet (1148, p. 689 *et seq.*).

In a strong but variable magnetic field, between pointed poles, bars of paramagnetic material, which are suspended on a thin horizontal silk thread, seek to place themselves, just as do ferromagnetic bars, parallel to the lines of force in the direction of the line connecting the poles, while rods of diamagnetic material tend to assume a position perpendicular to this position. If, it is assumed that the position of equilibrium produces the torsion of the filament, then a comparison value for the magnitude of μ can be obtained from the number of vibrations per second about its position of rest. Its liquid can be enclosed in tubes, and the differential effect between empty and full tubes be observed, according to Wilson (1634). According to Quincke (1265), in investigating the permeability of fluids, the rise of the fluid level is observed in a tube which is brought between the poles of a strong electromagnet. Other methods depend on the

measurement of the force with which a bar of the material under investigation, or a tube filled with the fluid in question, is attracted or repelled in a strong magnetic field. The force is measured, according to Faraday (443) and Wiedemann (1617), by means of a torsion balance which swings about a vertical axis, or, according to Meyer (758), Voigt and Kinoshita (1570), McLennan and Wright (1021), Finke (451), by means of a fine balance swinging about a horizontal axis. Investigations according to the former method have been carried out by Pfaff (1230) on a large number of rocks of the region on the right bank of the Rhine in Bavaria.

Other methods which are of practical importance in determining the permeability of rocks, depend upon their magnetizability in brines through which currents flow, since greater quantities

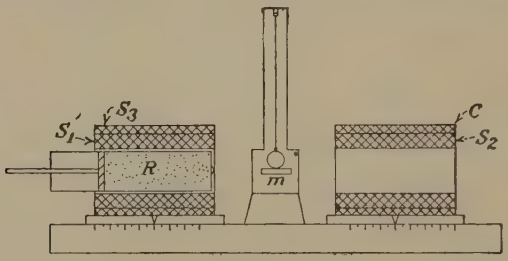

FIG. 33.

of material can be tested simultaneously and therefore average values obtained.

The coils are used with either direct or alternating current. With direct current, the increase or decrease of the magnetic field surrounding the coil, due to the introduction of ferromagnetic, paramagnetic, or diamagnetic cores, is determined; while with alternating current the change of inductance upon inserting the coil is measured.

The first method was employed by Rücker (1309) to compare the permeabilities of rocks.

A similar arrangement, which is represented graphically in Fig. 33, has been used by Ambronn since 1921. A magnetic needle m swings free in a horizontal plane. Its position of equilibrium is read in the usual manner with mirror and scale. S_1 and S_2 are two coils of a large number of turns, through which a variable direct current flows in opposite directions. By moving the coils S_1 and S_2 along their axes on two bars, their effect on

the magnetic needle m can be regulated by adjusting the magnitude of their comparative permeability and equalizing their distance from m. For the last adjustment, coil S_3 is used. Part of the main current flows through this coil and a constant resistance, giving an adjusted electromagnetic symmetry for all current strengths in S_1 and S_2. If a tube R, filled with the sample to be tested, is now inserted in one of the coils S, the equilibrium of the magnetic needle will be disturbed, because of the difference in permeability of the sample under examination and that of the air or other comparison material in the other coil. The tube R can also take the form of an elongated ellipsoid of rotation. Equilibrium will be restored again by the additional field generated by means of the coil C, and so equalized that the needle m will return to its position of rest. The direction and strength of the current in the coil C necessary for the restoration of the equilibrium then gives a measure of the permeability of the substance under consideration. Either the permeability can be calculated from the dimensions of the apparatus or a relative value can be obtained through comparison with the permeability of known substances.

Since, in general, specimens of size and form suitable for insertion in the coils cannot be cut from rocks, in view of time and cost, the samples are investigated in pulverized form. Mixtures from a greater mass material can then be used for the average sample. The air space between the individual rock fragments, however, can influence the results. This error may be avoided if the sample is pulverized in a fluid of almost the same permeability. This method is applicable in practice if a number of standard fluids of graduated permeability are prepared (see Rücker (1309)) and those two selected whose permeability changes least upon the addition of the substance to be tested.

The methods of Heydweiller (720) and Bavink (138) for measuring the magnetic permeability by means of alternating current depend upon the fact that the self-inductance of a coil is dependent upon the permeability of a core introduced into it. For the measurement of small permeabilities, however, it is often desirable to measure the change in the inductance of two rigid coils either moved close together or placed within one another, due to the introduction and removal of a core of the substance under investigation. Hughes (748) and Rücker

(1309) describe an induction balance constructed on this basis. While alternating current was employed for these measurements, Stutzer, Gross and Bornemann (1496) used intermittent direct current with corresponding arrangement of coils. In these methods, however, if the samples possess a considerable electrical conductivity, eddy currents which may be induced in them can vitiate the measurements, unless special precautions are taken, and the loss of energy through such eddy currents is eliminated by measuring the phase displacement of the alternating current in the coil. Some hysteresis phenomena act in the same way. The permeability measurements by direct current are to be preferred since the earth's magnetic field of force corresponds essentially to the magnetic field of a direct current.

In making measurements with alternating current, it is assumed that the permeability of the rock is independent of the magnetizing force, and that hysteresis losses are negligible. This assumption appears to be permissible in the case of most ordinary rocks. In Table VII are collected the susceptibilities $\varkappa$ (corresponding to $\mu = 1 + 4\pi\varkappa$) for a number of rocks. These values can serve only as arbitrary examples, since the value from one location to another fluctuates within wide limits. According to Bauer (128), comprehensive systematic investigations on the magnetic properties of the rocks of all countries should be made.

TABLE VII.—SUSCEPTIBILITIES OF ROCKS[1]

Material	$\varkappa \cdot 10^6$	Material	$\varkappa \cdot 10^6$
Ankerite	24	Limonite	220
Arsenopyrite	237	Magnesite	6
Augite	133	Magnetite	97,350
Azurite	40	Malachite	34
Barite	0	Olivine gabbro[2]	5,600
Basalt[2]	600	Psilomelane	268
Calcite	0	Pyrite	4
Cassiterite	88	Pyrolusite	128
Chalcopyrite	32	Pyrrhotite	7,018
Chromite	244	Quartz	0
Dolomite	1	Rhodochrosite	380
Fluerite	0	Rhodonite	458
Franklinite	35,640	Serpentine	1,274
Gabbro[2]	3,300	Siderite	331
Galena	0	Speculacite	3,215
Hornblende	122	Sphalerite	58
Ilmenite	30,740	Wolframite	241

[1] After Stutzer, Gross and Bornemann (1496); [2] After Rücker (1309).

In general, the permeability of rocks appears to increase slowly with rising temperature. At a definite temperature, which is characteristic for each material, the strong ferromagnetic permeability vanishes very suddenly. With iron this critical temperature (Curie's point) lies at about 750° to 800°. According to Wologdine (1645), the ferromagnetic properties of Fe_3O_4 vanish at 515°, of pyrrhotite at 300°, of Fe_3C at 180°, of $2Fe_3C$-$3WC_2$ at 80°, of franklinite at 61°, of Fe_3F at 445°, while Kunz (878) finds for hematite a strong change in the magnetic properties with increasing temperature. These temperature variations have a significant bearing on the question of the depth in the earth's crust at which strongly magnetizable masses can still obtain, because of the increase of temperature with depth. Rücker (1309) assumes from these considerations that the bed below which the ferromagnetic properties may lose their importance, because of high temperature, lies at a depth of about 200 km. The influence of pressure on the magnetic properties of magnetite was investigated by Welo (1598*a*).

In crystals, according to Sano (1344), Meslin (1088), Voigt and Kinoshita (1570), Smith (1457), Pascal (1210), the permeability can be dependent in a high degree upon the direction of the lines of force with respect to the main crystallographic axes. According to Lutteroth (1004), the dependence of the permeability upon temperature varies also according to the direction of the crystallographic axes. Turmlirz and Luggin (1552) also find "residual magnetism" phenomena in rock crystal. Voigt (1569) gives much literature on this question, and numerical values for numerous crystals. Since in rocks the small crystals, however, are almost entirely heterogeneously distributed, only the average value comes into consideration.

Rock Magnetism.—As the permeability of rocks varies within wide boundaries according to their composition and the origin of the formation, the residual magnetism of the individual rock bodies also varies. Generally one can easily differentiate two forms of origin of the permanent magnetism. Rocks of plutonic origin could assume permanent magnetism at that period of their cooling when they passed under their Curie's conversion point corresponding to the momentary value of the earth's magnetic field in which they were found. Melloni (1080), Förstemann (470), Folgheraiter (462), Agamemnone (10), Mercanton (1084), Chavallier (300), have attempted to derive,

in cases where one can assume such an origin, the present direction of the earth field from the kind of magnetization of such rocks. Corresponding investigations have been instituted by Brunhes and David (258) on clay layers which had been burned by basalt flows. The results are very contradictory. Corresponding magnetizations, assumed in firing, have also been established in antique pottery; Gherardi (543, 544), Folgheraiter (463, 464, 465, 466), Agamemnone (10), Mercanton (1083, 1086), Chevallier (299) have attempted to deduce the angle of dip at the time at which it was first burned. Laboratory investigations by Förstemann (470), Folgheraiter (462), Allen (20, 21), indicate that these assumptions in themselves may be admissible.

On the other hand, it has been found at the end of the eighteenth century that various individual blocks of rock and cliffs of crystalline, especially eruptive or intrusive, rocks mostly showed irregularly distributed magnetic polarity. The numerous investigations of Förstemann (470, 471), Melloni (1080), Zaddach (1655), von Trebra (1547), Wurm and Zimmerhackel (1652), Reich (1284), Oddone and Sella (1193), Oddone and Franchi (1192), Pockels (1241), Gaetano and Platiana (494), Washington and Larsen (1580), Loewinson-Lessing and Mitkowitsch (977), Palazzo (1208*b*), bring out many examples of this phenomenon. Comprehensive collections of the older literature on rock magnetism are given by Zirkel (1664) and Meli (1079). According to the works of Pockels (1241), it may be assumed today that the possibility of a magnetization of this kind is connected with the magnetite content of the rock in question, and that the origin of the magnetism must be sought in flashes of lightning which strike those rocks and cliffs, almost always isolated, which show this kind of magnetization. Pockels (1241, 1242) also shows by laboratory experiments that these kinds of rocks can actually be artificially magnetized by a strong discharge of sparks from an electric machine. Also columns of basalt erected near a lightning rod showed strong permanent magnetism after flashes of lightning. This purely local permanent magnetization of single rocks and cliffs, therefore, does not possess obvious geologic importance.

Rocks do not seem to become permanently magnetized by remaining for a long time in the earth's magnetic field, however, without changes of temperature. Stones capable of magnetization in themselves in very ancient buildings, according to Förstemann

(470) and Gherardi (542), exhibit no magnetization, or only the original one which they had before their immurement, which seems to arise from the entirely disorderly magnetization of the individual rocks in antique structures.

Possibly a permanent magnetization of rock masses magnetizable in themselves would be caused by violent earthquakes, corresponding to the behavior of steel rods in the earth field under a strong blow. Chance observations by Tanakadate and Nagaoka (1517), Agememnone (10), Messerschmidt (1093), Bauer (111, 113), on permanent changes in the magnetic elements at stations in earthquake regions after violent earthquakes can perhaps support such an assumption.

In the selection of the position and surroundings of magnetic observatories, the possibility of a change in the magnetic elements because of rock magnetism within very limited areas compels the most careful testing of geologic conditions in order to have as homogeneous a field as possible; by a detailed magnetic survey, the actual relations must be enquired into in the most exact manner, as shown in the works of Neumayer (1161), Claxton (308), Stelling (1478), Linke and Angenheister (960, p. 416), Mathias (1052), Clark (307), Colin (310), Börgen (204), and Froley (491).

The Relations between the Subsurface Structure and the Anomalies of the Earth's Magnetic Field.—The search for, and the measurement of, the local anomalies of the magnetic field of the earth possess practical geologic importance in two directions. These investigations are used in the study of rock structure and tectonic relations, where scientific interest especially lies. Further, many economically valuable minerals and rocks differ in their magnetic permeability so notably from the rocks enclosing them that the study of the anomalies of the earth's magnetic field can serve for their discovery and limitation. The great number of such investigations on which publications have been made makes it impossible to cite this material here individually. Only a few examples will be singled out here, and for the rest reference will be made to the literature.

The utilization of magnetic surveys for geologic investigations has been discussed very thoroughly by Naumann (1153), who, however, would trace the magnetic disturbances to earth currents which are connected with the greater fracture-lines cutting deep into the crust of the earth. Helmert (688), in 1888, made

note of the connection of geologic phenomena with terrestrial magnetic anomalies. Nippoldt (1175), Haussmann (646), examined the new magnetic map of 1912 for Germany in regard to its utilization for inferences on the basic features of geologic structure in the region designated.

Individual parts of Bavaria were investigated by Pfaff (1229, 1230, 1232) as examples of the relations between the disturbances of the earth's magnetic field and the subsurface structure. His demonstration of the local anomalies by symbols may scarcely increase the clearness, however. The general limits to the utilization of terrestrial magnetism for geologic purposes

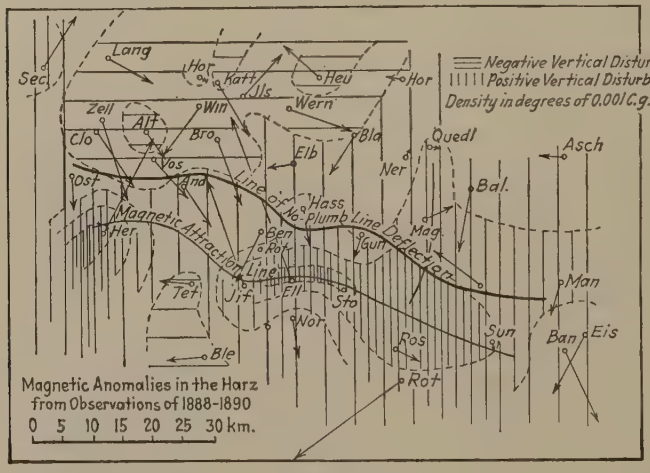

FIG. 34.

has been treated by Strahan and Cox (1490), as well as by Mathias (1050) and Angenheister (45).

The magnetic effect of mountain masses has been investigated in Germany at many places. The iron-rich eruptive and intrusive rocks of the mountain core have proved especially effective. The influence of the Alps and their crystalline core in the distribution of the earth's magnetic field was investigated by Kreil (870). The investigation of the magnetic effects of the mountain masses of the Harz by Eschenhagen (430) led to the little map printed as Fig. 34, in which the horizontal disturbance forces are recorded as arrows, and the disturbances of the vertical intensity are designated by isanomalies and shaded surfaces. The length of the arrow gives the horizontal intensity, while 1

mm. of its length indicates 6γ. It is noteworthy from the course of the magnetic axis, and especially from its branches running north-northeast, that evidently the magnetic influence of the Harz horst and its granite core is broken into fragmentary peaks. The close connection between the magnetic disturbances and the gravity disturbances measured in the same region is especially to be noted. The two axes run (Fig. 34) exactly parallel to each other in a surprising manner. Girard (550) also reports on a small anomaly within the Harz which, in his view, is attributable to the serpentine deposits. Nippoldt (1175*a*) reports on a new survey of the vertical intensity in the southeast Harz, which does not altogether agree with the older results given in Fig. 34. Böhmländer (199) and Schaper (1349) investigate the magnetic effect of basalt peaks in the Rhone region; Meyer (1096) gives a careful investigation of that of the Kaiserstuhl. Further magnetic-disturbance regions, especially those caused by eruptive rocks, have been worked up by Weber (1591) at Göttingen; by Haussmann (642) for the Channel region; by Hammer (629) for middle Württenberg with disturbances in the vicinity of Rauhen Alb; by Günther and Adami (595) for the Schwarzenstein at Trögen on the Saxon-Bavarian boundary; by Stöckl (1486) in the Bavarian forest, where the arrow clearly emphasizes the boundary line between gneiss and other formations; by Körber (859) in the Bohemian-Silesian border region; by Meyer (1098) in Silesia; by Göllnitz (570) in the vicinity of Dresden; by Zeisberg (1658) with comprehensive references to literature and by Wolff (1643) for the granitic Zobtengebirge. A magnetic-disturbance region near Aachen has been worked up by Haussmann (643).

Characteristic and very strong disturbances whose origin is still not entirely clear are to be noted in the northeastern provinces of Prussia. The most probable assumption is that great masses of magnetic rock, brought from Scandinavia by the ice during the Glacial period and irregularly piled up, are deposited in the subsoil. Other evidences, on the contrary, point to origins lying still deeper in the subsoil, and bring these anomalies into relation with the very great anomalies running through Russia with north-west south-east trends, and which are due to iron rich-plutonic rocks. There are reports by Schmidt (1378, 1388), Nippoldt (1180), and Errulat (427) on the measurement of these anomalies. Whether the magnetic disturbance in Hol-

stein, Mecklenburg, and Pomerania have an origin similar to those in east Prussia, or arise from salt tectonics is still a disputed question. Results of magnetic measurements on Holstein disturbances between Plön and Neumünster are offered by Schaper (1350). There are reports on magnetic investigations in Mecklenburg by Schuh (1402) and Moll (1131). Measurements under the direction of Ambronn, south of Heide, in Holstein, show the same sharply expressed anomalies with readings of over 50γ per kilometer. It cannot be decided with complete certainty whether the cretaceous or salt horsts, demonstrated by borings, with their very low permeability, are the origin of the disturbances. The east Prussian disturbances, on which Nippoldt (1181) reports in detail, also continue towards the east.

On the magnetic anomalies in Poland there are reports by Kalniowski (797). Fritsche (489), Meyen (1095), Schweizer (1416), Sludskij (1453), treat of an important magnetic anomaly at Moscow which is also manifested by gravity disturbances; Maydell (1065), Leyst (Passalskij) (951) a similar one at Odessa. In northern Russia, and in Finland, Sweden, etc., extraordinarily strong anomalies due to rocks with very high content of magnetite have been observed. In part these can be extremely dangerous for shipping, because of the compass fluctuations which they cause. Furthermore, Fritsche (488, p. 102 *et seq.*) offers reports on these anomalies; also Tillo (1541, 1542) (Russia), Lenz (942) (Bay of Finland), Tigerstädt (1540) (Jussar-ö), (1539) (in the Rapaviki region near Wiborg), Brodmärckel (250) (at Karlö, in the Bay of Bothnia), Carlheim-Gyllensköld (286) (Sweden), Alenius (18) (at Helsingfors), Ljungdahl (961) (southern Swedish coastal region and on the Väner-See), and (961*a*) (northern and central Sweden), and Odelsiö (1194) (in Sweden).

A very exact magnetic survey of the island of Bornholm has been made by Paulsen (1214). Figure 35 shows as an example the distribution of the horizontal components of the magnetic-disturbance vectors on the island of Bornhelm. The effect of the granite in the northern part of the island can thereby be clearly deduced as the origin of the magnetic anomalies. A completion of the measurements, especially to the southwest into the sea, has been supplied by Hammer (634).

In connection with their magnetic land survey of Great Britain, Rücker and Thorpe (1309, 1311, 1313, 1536) have made

an exhaustive examination of the different regions of magnetic disturbance found there, and report that they may be caused mostly by rock masses of higher magnetic permeability (basalt and the like). Anomalies in the Hebrides have been investigated by Field (450) and Harker (639), those in Northamptonshire and Leicestershire by Cox (320*c*).

In France, a special interest is taken in the great anomaly of the Paris Basin, striking south-southeast to north-northwest, which has been very carefully investigated by Moureaux (1138) and Eblé (379). Mourcaux (1141) also shows how this region of disturbance forms a single member of the entire distribution of the earth's magnetic field in France. Eblé (379) reports particularly that values of the local disturbance within this anomaly have not markedly changed from 1896 to 1922. Its north-northwest extension, according to Rücker (1309), and Rücker and Thorpe (1313), extends into the region of the British Isles. A range of iron-rich magnetic rock masses at greater depths may be assumed as the origin of this extraordinarily clearly developed disturbance zone. Magnetic disturbances in the Puy de Dome range have been worked out by Brunhes and David (259, 260). In other parts of France, magnetic disturbance regions are also found which have been investigated by Brazier (242), Tabesse (1505*a*) (Normandy), (1505*b*) (Loire), Dougier (357) (southeast France, left bank of the Rhone), (358) (Dauphiny, Savoy, and La Bresse), Maurain (1058) (Brittany).

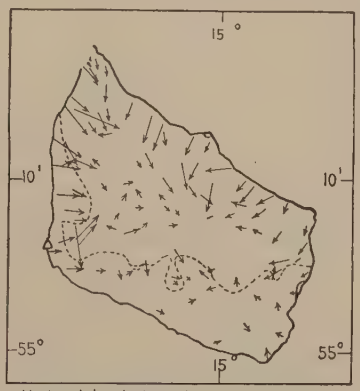

FIG. 35.

In Italy, magnetic anomalies have been recorded by Franchi (484*a*) and Palazzo (1207, 1208), as well as Folgheraiter (461) and Ricco (1292). Relative to Switzerland, see also Brückmann (254). The Mediterranean Sea is treated by Nordmann (1186). On Lake Balaton, Steiner (1475) carried out measurements which were compared with the gravity anomalies found by von Eötvös (400). On the border of the Hungarian plain, serpentine veins were magnetically measured by von Eötvös (401). Figure 36

shows the course of the horizontal components of the disturbance vectors along a perpendicular to the path of the measured profiles.

In North America, magnetic-disturbance regions are treated by Locke (975) (on Lake Superior), Nipher (1169) (in Missouri), Smyth (1459), Heck (655) (Alaska). The great national survey showed, for instance, according to Hazard (653), very numerous regions of disturbance. Creak (322) reports on magnetic disturbances in Australia. To the connection of regions of magnetic disturbance with subsurface structure in New Zealand, Farr (445) devotes special attention. Colin (310*a*) reports on magnetic regions of disturbance in Madagascar. The considerations on Asiatic and Japanese regions of disturbance by Naumann (1153) still have value today, independently of his theory of the production of magnetic anomalies by earth currents, which is no longer recognized.

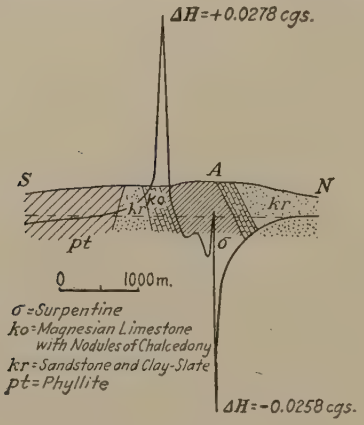

FIG. 36.

Further deductions will be devoted to the application of magnetic measurements to the search for deposits of economic value.

The older investigations of this kind were made for the detection of magnetic iron ores. Greiss (582), Tiberg (1538) discuss the physical-petrographic basis for this method. The latter turns his attention to the question whether one can safely differentiate magnetically disseminated magnetite from true magnetic iron-ore deposits. In general, in regard to this question, it is to be noticed that the conception of the "ores" is more an economic than a physical, chemical, or petrographic one. It conforms to the economic conditions at the time. A few percent of iron more or less, small quantities of injurious impurities (sulphur, quartz, and so forth), can determine the economic value of a deposit at the time, while they cannot be physically noticeable at all in the effects at a distance of the mass present. It amounts to this: that in effects at a distance, in general, the resultant proceeds from the actual effective masses and the specific energy per unit volume. *Therefore, the most careful consideration*

of the attraction of all other attainable substances is necessary for the economic valuation of geophysically established deposits.

The carrying out of magnetic measurements in the search for iron-ore deposits with simple instruments (compass with deflection-magnet and dip-needle) is treated in detail by Thalén (1522, 1523), Dahlblom (326), Tiberg (1538), Kjellberg and so forth (806), Zsigmondy (1670), Uhlich (1555), Smock (1458), Smyth (1459), Hotchkiss (743), who give detailed theoretical and practical examples for the determination of the shape, depth and boundaries of ore masses which are detectable with these simple contrivances. The results of such magnetic measurements on iron-ore deposits in Sweden are found, for example, in Carlheim-Gyllensköld (285, 287), Thalén (1521).

Comprehensive investigations with modern instruments have been carried out on the well-known anomaly of Kursk, in Russia, in the past decade; the original observation material, assembled by Leyst (953) in 10 years' work, was afterward lost at his death. The new measurements carried out under the direction of Lasareff, including data on corresponding gravity disturbances which were found and measured, show that in the province of Kursk two series of highly magnetic rocks strike parallel to one another in a northwest-southeast direction. In this very problem the discussion relative to the question mentioned above, as to how far one may draw conclusions on the economic value of the occurrence from the results of the magnetic measurements, has been carried out in every way in the widest sense. The borings put down in the meantime, so far as can be ascertained, seem to have encountered rocks carrying a very high percentage of magnetite at about the depth magnetically determined, without, however, making possible a final decision on the economic value of the occurrence. From the very extensive literature on the magnetic measurement of these occurrences, the works of Moreaux (1140), Lasareff (910, 911, 915), von Bubnoff (265), Schewjakoff (1361), Backlund (85), Himmelfarb (722), Gubkin (590), Tams (1512), Dlougatch (352), Archangelski (56), may be named.

Magnetic measurements on the much shallower bedded iron-ore deposits of Krivoi-Rog have been published by Weinberg (1594), Passalskij (1212, 1213) (reviewed by Hazard 652, Leyst 951), and Bachurin (84*a*). In America, reports on magnetic investigations on iron-ore deposits have been made by

Hotchkiss (743), Smyth (1459), Heck (655, 656), Broderick (249), Laylander (926*a*).

Expositions of a general character are given by Haanel (618), Königsberger and Gallus (840), Reich (1289*a*), Heiland (674), Möller (1132*a*), Wilski (1632*a*). Heiland gives an especially clear example of the magnetic measurement of a magnetite seam at Berggiesshübel, which is inserted here as Fig. 37. Further, compare Naumann (1155), as well as textbooks on ore deposits, for instance, Krusch (875, pp. 96 *et seq.*).

Besides the search for iron ores, magnetic investigations can also serve in many cases for the location of other valuable ores in which magnetite occurs only as an accessory constituent. If ores which are non-magnetic in themselves occur in seams, in beds, or in the contact zone of eruptive rocks, then the magnetic investigation of the geometric form of the eruptive masses,

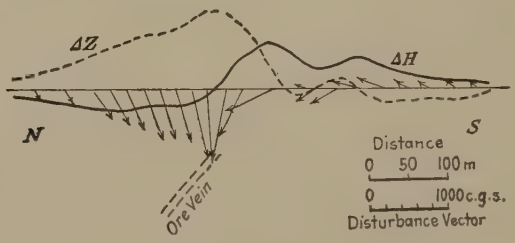

FIG. 37.

almost always containing magnetite, can often furnish indirect evidence of the extent of a deposit, as has already been noticed by Fox (477), as well as by Aldrich (17), and by Turley (1553). Also, weakly magnetic iron ores (limonite, siderite, etc.), in masses of great extent, and occurring at not too great depths, can frequently be investigated with success by magnetic measurements carried out very carefully and exactly, as Gibson (547), for instance, shows. The measurements of Wagner (1571), however, offer especially important bases for further investigations in this direction. In the Aachen and Erkelenz coal region, Reich (1289*c*) attempted to connect the magnetic measurements with the subsurface structure.

In contrast with these measurements used in searching for materials whose permeability is greater than that of their surroundings, magnetic precision measurements can also be used for finding and limiting those masses whose permeability is less

than that of the rocks surrounding them. Schuh (1402, 1403) reported on these methods for the first time as a means for seeking salt domes in the subsoil of the North German lowland, and sought to prove the usability of fine magnetic measurements, especially the vertical component alone, by means of Schmidt's field balance in examples. The technique of measurement was later further developed, on which there are reports by Moll (1131), Ambronn (33), Nippoldt (1176), Haalck and Brinckmeier (617), Königsberger (837), Heiland (673, 674). The two curves in Fig. 38 are taken from the last publication. They may make the connection between the geologic structure of the salt domes and the value of the vertical component of the earth magnetism clearly recognizable. It is seen in these two curves how the nonmagnetic or even perhaps weakly diamagnetic salt masses push out the lines of force of the earth field into the more strongly magnetizable rocks surrounding them, and thereby produce a region of decreased density of lines of force, and thus decreased vertical intensity, over the salt dome. To this region of diminished vertical intensity over the salt dome, there must naturally correspond regions of increased intensity in its vicinity, since the lines of force of the earth's field can only be displaced by all magnetic or magnetizable deposits, but not be diminished nor increased.

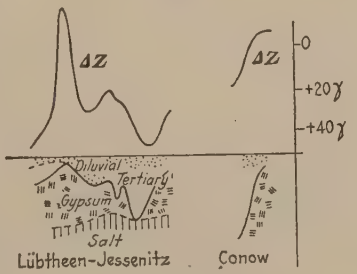

FIG. 38.

The use of magnetic measurements for explaining the tectonics of a region is shown in the works of Haalck and Brinckmeier (617), carried out under the direction of Ambronn, and the investigations of Reich (1288) in upper Silesia. Pfaff (1232) shows connections between tectonics and extent of coal occurrences in Bavaria. Krahmann (867*b*) reports on measurements on a lignite occurrence near basalt, the practical value of which is slight, since specially designated reference points almost never agree in position on magnetic and geologic maps.

Formulæ for the magnitude of the disturbances of the horizontal intensity, vertical intensity, and declination produced by ellipsoidal and other deposits in the subsoil, are given by Thalén (1521–4), Smyth (1459), Uhlich (1555*a*), Carlheim-Gyllensköld

(287), Griesser (584), Königsberger (837), Haalck (616*a*). These relations become clearer if they are derived for two horizontal components of the magnetic-disturbance force which are perpendicular to each other, whether it be for the north-south and east-west component, or for the directions lying parallel and perpendicular to the normal direction of declination.

The possibility of finding and delineating underground salt domes by means of magnetic measurements is also of great importance indirectly in the detection of oil deposits (see, for instance, Ambronn 27*a*), since these are bound up in many economically important regions with the occurrence of salt intrusions. Other connections between oil occurrences and magnetic anomalies, suggested by Becker (146), have no real basis according to Tarr (1518). The delineation of isogons is generally unsuitable in itself for all practical magnetic work. Kalitsky (798) also has taken this question into consideration.

From some points of view, (see Sundholm (1501)), it is noteworthy that the magnetic inhomogeneities in the crust of the earth can influence the temporary fluctuations of the earth's magnetic field in these regions. So far, it has been a question of short periodic fluctuations; in the section on the earth current there will be an opportunity to discuss them more clearly. Pfaff (1229, 1230), Maurer (1064), Chree (301), have been working on the influence of longer periodic fluctuations, especially the secular variations due to locally disturbed conditions of the earth's crust, without, however, drawing any special practical conclusions therefrom. On the other hand, Passalskij (1212, 1213, 951) considers this same question especially noteworthy, and derives strong formulae for the influencing of the temporal variations by local anomalies of the earth's magnetic field.

CHAPTER IV

THE USE OF RADIOACTIVE AND ATMOSPHERIC-ELECTRIC MEASUREMENTS FOR GEOPHYSICAL PROSPECTING

Investigations on radioactive substances come into consideration in applied geophysics in two ways. Rocks which exhibit an especially high content of radioctive material constitute raw material whose production has a high economic value. Springs with high emanation- or radium-content are of practical importance for medicinal purposes, when they are used directly as baths or drinking cures, or manufactures are made from their emanations.

In lesser amounts, however, radioactive substances are also present in all other rocks, waters, and gaseous constituents of the crust of the earth. Their detection in vanishingly small quantities is physically relatively easy, and therefore several methods have been developed for drawing conclusions on the geologic structure and origin of the formations of the uppermost crust of the earth from the kind and manner of their distribution, and their relations in the individual rock formations, etc. Since gaseous transformation products of the radioactive materials present in the uppermost formations of the earth also go out into the atmosphere through soil respiration, and there influence the phenomena of atmospheric electricity, one must investigate whether perhaps some conclusions on the structure of the solid subsoil in the vicinity of the place of observation cannot be obtained through measurements of atmospheric electricity.

The Properties of Radioactive Materials and Their Measurement.—The properties of radioactive materials and their measurements have already been treated in a great number of comprehensive works. Here may be named the comprehensive work of Meyer and von Schweidler (1100), the textbooks of Hevesy and Paneth (719), Curie (324), Rutherford (1333), Meyer (1099*a*), and Kovarik and McKeehan (862*a*); further, the section on radioactivity (p. 1213 *et seq.*) and earth electricity (parts of p.

1386 *et seq.*) in Müller-Pouillet's Lehrbuch der Physik und Meteorologie (1148); the methods of measurement in the field of radioactivity are treated by Makower (1038), as well as by Geiger and Makower (523). The radioactivity of soil and springs has been discussed by Gockel (560) on the basis of comprehensive literature data, and with addition of numerous tables; a concise review is given by Ludewig (993).

Only those facts and methods of measurement may be mentioned here which may be of especial importance for the investigations of applied geophysics. From a radioactive base there develops, according to the dissociation hypothesis of E. Rutherford and F. Soddy, in the course of time, radioactive derivatives. This dissociation is accompanied by the emission of different kinds of rays, which carry with them extraordinarily great energy, and which therefore are especially suitable for the detection and classification of the material concerned, and can be thus used. Besides the α-rays, consisting of positive helium atoms, negative electrons are emitted as β-rays. The dissociation is also connected in many cases with the emission, for the greatest part, of very hard Röntgen rays, called γ-rays.

On the average, in unit time, the same fraction of a very great number N of atoms of a radioactive initial substance continually dissociates into atoms of the next material, with emission of characteristic rays. Therefore

$$\frac{dN}{dt} = -\lambda N,$$

where λ indicates a characteristic dissociation constant for each radioactive element. The number N_t of the atoms of the mother substance still unchanged at the time t is, then,

$$N_t = N_0 e^{-\lambda t}.$$

Within the time $1/\lambda = t$, the average life duration, $1/e = 0.36788$ of the initial substance is decomposed. On the other hand, the half value is the space of time within which exactly half of the mother substance is decomposed. Since the decomposition products of radioactive materials are mostly again active and decompose with another half-value period, according to an exponential law, with characteristic λ, one can calculate, with the knowledge of these half-value periods, or decomposition constants, to each time how much of a mother substance present

at the beginning is present at any particular time, and how much of each derivative. In the detailed expositions named above, time tables for this decomposition can be found.

If the radioactive base has already been so long with its derivatives that now, in a unit's time, exactly as many atoms are newly formed as are decomposed from it, then the derivatives are found in radioactive equilibrium with their base. The relative number of atoms of the individual materials of the decomposition series contained in this condition of equilibrium is inversely proportional to the decomposition constant, or half-value period.

The initial substances of the radioactive series are uranium and thorium. From uranium there are two series of derivatives. The most important materials of these series are given in Table VIII, with their half-value period and the kinds of rays appearing in the decomposition of each. Omitted steps are indicated by a dash (—).

TABLE VIII

Material	Half-value period	Rays emitted
Uranium	5×10^9 years	α
Ionium	ca. 10^5 years	α
Radium	1,750 years	α, β
Radium emanation	3.86 days	α
Radium A	3.05 minutes	α
Radium B	26.8 minutes	β, γ
Radium C	19.6 minutes	α, β, γ
Radium D	ca. 16 years	β, γ
Radium E	4.86 days	β, γ
Radium F	136 days	α
Lead	Stable	
Uranium	5×10^9 years	α
Actinium	ca. 30 years	(α)
Actinium emanation	3.9 seconds	α
Actinium A	0.002 seconds	α
Actinium B	36.1 minutes	β, γ
Thorium	ca. 1.8×10^{10} years	α
Thorium X	3.64 days	α
Thorium emanation	54.5 seconds	α
Thorium A	0.14 seconds	α
Thorium B	10.6 hours	β, γ
Thorium C	60.4 minutes	α, β

Besides the members of this series, some alkalies with low atomic weight, potassium and rubidium, have been designated as weakly radioactive substances. For geological investigations this property has attained no importance to date. Comprehensive reports on the radioactivity of the alkalies are given by Elster and Geitel (390), Hahn and Rothenbach (624), Neuburger (1160), Hoffmann (732).

On a general radioactivity of all materials much has been done; we mention only Hoffmann (731) and Kolhörster (855, p. 36), with negative results so far.

The concentration of radioactive materials is generally given in grams per gram or per cubic centimeter of total substance. For the radioactive gas, radium emanation, which is important in practical work, a special measure, the *curie*, has been introduced. A curie is that quantity of emanation which is in equilibrium with 1 g. of radium. 1 curie Ra-em (radium emanation), at 0° and 760 mm. pressure, fills the space of 0.6 cmm. and weighs some $6 \cdot 10^{-6}$ g. On the complete disintegration of the $1.7 \cdot 10^{16}$ atoms of one curie Ra-em, the amount of heat evolved is 38.60 cal. The concentration unit of the emanation is the (older) practical unit corresponding to $3.64 \cdot 10^{-10}$ curies per liter.

The measurement of radioactive materials can be made with the balance, by determination of the ionization in the gases excited by its rays, or calorimetrically from the quantity of heat produced by its change. However, in practice, weighing comes practically into question only for the two initial substances of the uranium and thorium series, also for radium and Ra-em. By far the most important method is the measurement of ionization. Calorimetric measurements scarcely come into consideration for our purposes. We can limit ourselves here to the study of the electrical method of measurement of ionization to which special reference is made in the paper of Geiger and Makower (523) on methods of measurement of radioactivity.

If gases are permeated by α-, β-, or γ-rays, then positive and negative ions are produced in them by splitting up of the neutral gas molecules. Under the effect of an electric field the two kinds of ions begin to move in opposite directions toward the electrodes producing the field. An electric current thus flows through the gas which, however, only obeys Ohm's law for stronger ionization and weak field. Since, in a state of equilib-

rium, no more ions can be attracted by the electrodes in unit time than are produced by absorption of the rays in the same time, with increasing field strength, a limit will finally be reached at which all the ions produced reach the electrodes, where they give up their charges. A further increase of voltage can produce no stronger current in the gas, as long as no impact ionization appears.

The current is saturated. This condition is desired in many measurements because of its theoretical simplicity. Opposing this is the tendency of ions of different signs to unite and form neutral molecules. This tendency increases with the square of the ionic concentration. Therefore, the field strength necessary for the attainment of the saturated current also rises very rapidly with increasing ionization. The diffusion of the ions to the walls of the receptacle where they give up their charge must also often be taken into consideration.

The α-rays of 1 g. of the metal radium, if they were completely used up in ionizing a gas, could maintain a current of $2.42 \cdot 10^6$ electrostatic units, or $8 \cdot 10^{-4}$ amperes. This is based on the assumption that $3.5 \cdot 10^{10}$ particles are emitted per second, and that each particle produces 145,000 ions with a charge of $4.77 \cdot 10^{-10}$ electrostatic units. The α-particles of a curie of emanation, on the other hand, would yield a saturation current of $2.74 \cdot 10^6$ electrostatic units, or $9.1 \cdot 10^{-4}$ amperes. The practical unit of Ra-em is defined as that quantity which yields, without its transformation products, a saturated current of exactly 1/1,000 electrostatic units.

In the Freiberg session of 1921, a new concentration unit, the *eman*, equal to 10^{-10} curies per liter, was introduced, according to Ludewig (994), so that one practical unit = 3.64 emans.

The power of penetration of the different kinds of radioactive rays, and the energy accompanying them, is characteristic for each radioactive element. The table below gives the range of

TABLE IX

Uranium	2.50 cm.	Actinium	3.56 cm.
Ionium	3.07 cm.	Actinium emanation	5.57 cm.
Radium	3.30 cm.	Thorium	2.72 cm.
Radium emanation	4.16 cm.	Thorium X	4.30 cm.
Radium A	4.75 cm.	Thorium emanation	5.00 cm.
Radium F	3.85 cm.		

the α-particles (positively charged helium atoms) given off by various radioactive substances, in air at 15° C., 760 mm. pressure (1100).

The β-rays are characterized by their low penetrating-power, being readily absorbed by aluminum foil; the higher the speed with which they are emitted, the more penetrating they are. With different absorbing materials, the absorption is approximately inversely proportional to the thickness of the material. The absorption coefficient μ is the reciprocal of the thickness of an aluminum sheet which reduces the intensity of the rays to $1/e = 0.36788$ . . . times the initial intensity, while the thickness of an aluminum sheet which diminishes the intensity of the ray to one-half is designated as the *halving* thickness D. Since the β-ray of the radioactive material is often not homogeneous, but composed of several groups of rays, Table X gives the *halving* thickness for the individual components in a few cases.

TABLE X

Radium:	$2.2 \cdot 10^{-3}$ cm. Al
Radium B:	$5.3 \cdot 10^{-2}$; $8{,}6 \cdot 10^{-3}$; $8 \cdot 10^{-4}$ cm. Al
Radium C:	$5.3 \cdot 10^{-2}$; $8{,}6 \cdot 10^{-3}$ cm. Al
Radium D:	$1.26 \cdot 10^{-4}$ cm. Al
Radium E:	$1.61 \cdot 10^{-2}$ cm. Al

Exactly similar methods are applicable to the γ-rays (Röntgen rays). The *halving* values of the γ-rays for some radioactive materials are contained in Table XI. For very penetrating γ-rays, the *halving* value is also given for lead.

TABLE XI

Radium B:	$3.0 \cdot 10^{-3}$; $1.73 \cdot 10^{-2}$; 1.36 cm. Al
Radium C:	6.03 cm., Al 1.39 cm. Pb
Radium D:	0.015; 0.70 cm. Al
Thorium B:	1.9 cm. Al
Thorium D:	7.22 cm. Al; 1.5 cm. Pb

By measuring the range of the α-rays and the halving thicknesses of the β- or γ-rays, radioactive materials of unknown composition can be analyzed.

The radioactive solids can be compared, according to Elster and Geitel (387, 1100, p. 221 *et seq.*) thus: equal weights of the

finely pulverized bodies are placed on a capsule in an ionization chamber, and the ionization produced is measured. The substances should be spread out as evenly as possible. In order to compare the influence of the gaseous dissociation products which, after the introduction of the sample into the ionization chamber, permeate it and deposit their derivatives, which radiate continually, on these walls, one must either wait for the measurement until a position of equilibrium is approximately reached (after about 3 hr.) or carry out the measurements at equal intervals of time.

A simple apparatus suitable for such coarse measurements is shown in Fig. 39. The electroscope 1 (constructed as a bifilar electromotor, according to Wulf) is fixed on a box 3 of conducting material, so that the support 2, with the attached charging rod 5, projects into the interior of the box 3. On the bottom of the dispersion chamber is fitted a removable capsule 4, into which the substances to be tested are introduced in similar layers. According to the process of Elster and Geitel, it is customary to use 125 g. as the normal quantity. To make a simple rough analysis of the ray itself, the preparation can be covered with aluminum foils of suitable thickness. If it is desired to use only β- and γ-rays, the dispersion chamber must be separated by a sufficiently thick (some 0.03 mm.) aluminum foil 6 from the space into which the sample is introduced immediately beneath the foil.

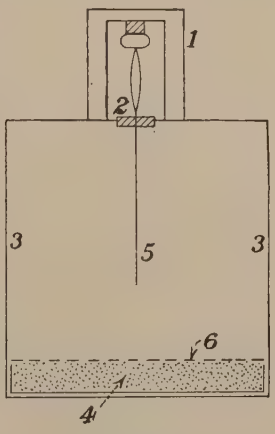

FIG. 39.

If it is desired to measure the activity of the surface formations *in situ*, without removing the sample from the soil, then, according to Ambronn, the basal plate and the capsule are removed from the box 3 and the box is placed immediately on the cleared and level ground. In order to be able to carry out such measurements rapidly, the cubic content of the box 3 must be about 20 l. Care must then be taken to have a thorough mixture of air in the box, in order to obtain the most uniform ionization possible. Irregularities of this kind in the measurement can cause transient fluctuations in the quantity of the emanation coming out of the

soil. A very thin aluminum foil on the bottom of the ionization chamber is a protection against this, but in practice it is difficult to keep this intact when using the apparatus in the field.

In order to make possible quantitative determinations and an exact separation of the different radioactive substances contained in the rocks, the rock samples, according to Boltwood (202) and Mache, Meyer and von Schweidler (1017), must be decomposed and dissolved according to known chemical methods. The radioactive materials in solution are then investigated by the methods used for the investigation of fluids.

Joly (778) avoids the complicated wet decomposition when he fuses the very finely pulverized mineral with potassium-sodium carbonate and boric acid in a platinum crucible with air excluded. The emanations quantitatively escaping are sucked off into the ionization chamber of an electroscope previously exhausted of air and its emanation content measured. When the melting is repeated after about three weeks, the quantity of the radium emanation which in the meantime has again almost come to equilibrium, is determined, and thus the radium content of the melt itself. A description of these methods, together with numerous critical notes are given by Büchner (267), Mache and Bamberger (1014).

Joly (776, 777, 784) also describes a similar method for determining the thorium content of rocks, which is based on the fact that no thorium is contained in the part of the above-described melt which is soluble in alkali; thus with solution of the material in water much more remains in the insoluble residue. After pulverization, the residue is dissolved in concentrated hydrochloric acid and the thorium emanation developing from the solution is used in a suitable manner for the determination of its thorium equivalent by means of an emanation electroscope. Fletcher (460) expelled the emanations by heating in an electric arc.

Ludewig (996), Dorcey (353), and Hess (716) used the γ-ray for the determination of the radium content. Hess describes particularly an apparatus suitable for large quantities of material.

The amount of radioactive substances in fluids, springs, etc., is determined by measurement of its emanation content or the quantity of emanation currently forming. The emanations follow Henry's law, *i.e.*, the portion dissolved in a fluid is propor-

tional to the partial pressure of the emanation in the gas space over the fluid. With known fluid and gas volumes, the distribution in equilibrium can therefore be calculated quantitatively if the solubility of the emanation in water (or other liquid) is known. This is given in Table XI*a* in relation to the temperature, according to Meyer and Mache (1100, p. 326) (see also Hevesy, (718)). If V denotes the volumes in contact with one another, Em the quantities of emanation for water W, or air L, then the fraction will be

$$\frac{Em_W \cdot V_L}{Em_L \cdot V_W} = l.$$

TABLE XI*a*

Temperature in degrees Centigrade....	0	5	10	20	30
	0.510	0.420	0.351	0.254	0.195
Temperature in degrees Centigrade....	40	50	70	100	
	0.159	0.138	0.117	0.108	

In some other solvents much higher solubilities of l have been found at a temperature of 18° to 20° C.

TABLE XII

Fluid		Fluid	
Olive oil and similar oils	28	Vaseline oil, petroleum	10
Carbon disulphide	23	Paraffin oil	9
Toluol, xylol, benzol	13	Glycerine	1.7

While the ratio of solubility remains independent of the pressure within wide limits, its dependence upon the temperature is very great, since the solubility of the emanations in all fluids increases rapidly with falling temperature. The solubility l, in relation to the temperature, can be represented by the formula $\iota = A + B \cdot e^{-\nu\vartheta}$, where e indicates the base of the natural logarithmic system and ϑ the temperature in hundredth parts of the total temperature interval between the melting point and the boiling point (at atmospheric pressure), while A, B, and ν signify the characteristic constants of the solvent in question.

The following table contains the values, according to Meyer and Schweidler (1100, p. 327), of the constants A, B, and ν, as well as the melting and boiling points for a number of substances used as solvents for radium emanations.

TABLE XIIa

Substance as solvent	Melting point	Boiling point	A	B	ν
Carbon disulphide, CS_2	−110°	46.3°	13	900	0.054
Ethyl ether, $C_4H_{10}O$	−117.6	34.6	10	700	0.055
Toluol, C_7H_8	− 92.4	110.7	2	125	0.045
Chloroform, $CHCl_3$	− 63.2	61.2	9.5	90	0.043
Ethyl alcohol, C_2H_6O	−117.6	78.4	2.5	86	0.046
Acetone, C_3H_6O	− 94.6	56.1	4	68	0.046
Ethyl acetate, $C_4H_8O_2$	− 83.8	77	4	66	0.048
Xylol, C_8H_{10}	55	139	1	68	0.045
Water, H_2O	0	100	0.105	0.405	0.050

Thus, water is by far the poorest solvent for radium emanations in comparison with the other solvents tabulated above.

The best method of measuring radium emanations in aqueous solution is to boil the water with air in a closed system, thus driving the emanations into the air where they may be measured. In cases where conditions make this difficult—as, for instance, when investigating springs in the country—one must be content with agitation, by repeated pumping of the air through the water. The volume of air used in this operation should be substantially greater than the volume of water.

The time elapsing between the taking of the sample of water to be investigated and the measurement must be accurately known, in order to be able to correct for the quantity of emanation dissociated in the meantime. If, on the other hand, the radium content of the solution is to be determined, then all the emanation must be removed from the solution by aerating with a large volume of fresh air, and the solution must then be allowed to stand carefully sealed for about three weeks. At the end of this time, the emanation will again have established equilibrium with the radium content. The emanation content then measured in curies gives at once the quantity of radium present in the fluid in grams.

A survey of the manifold apparatus which have been constructed for shaking the emanation out of the fluid, and for introducing the same into the ionization chamber of an electrometer, are given by Meyer and von Schweidler (1100, p. 233 *et seq.*). The method of measurement is treated by Becker (141), the necessary corrections by Berndt (175). Appropriate

apparatus, called a "fontaktoscope" or "fontaktometer," have been built by Engler and Sieveking (393, 394, 395, 1446) (agitation), Mache and Meyer (1016, 1099) (aeration through water), von Weszelsky (1603) (circulation method), Hammer (635, 636), Becker (139). In some of these instruments the mixing space is connected directly with the ionization chamber. Ludewig (991) lets the water containing emanation drip on the wall of the ionization chamber.

The amount of thorium and actinium emanations contained in fluids must be determined (267, 1014, 1100) by continuous-current methods, since the velocity of dissociation is too great for static methods. With thorium emanations, determinations can be made, according to Gockel (560, p. 75), also by its long-lived dissociation product thorium A ($T = 10.6$ hr.).

As an electrometer, the gold-leaf electroscope is no longer adequate. When not working in the laboratory with the quadrant electrometer, the bifilar electrometer described by Wulf (1649, 1650, 1651), Kolhörster (857) (very small capacity), and Lutz (1008), is used. It can be transported very safely. In it the repulsion of a fine quartz filament or a thin wollaston wire from its support (Fig. 40), or the mutual repulsion of two of these fine filaments supported parallel to one another and close together, for instance, by a quartz guard (Fig. 39), are read through a microscope, and give a measure of the voltage produced. The two filaments are restored to their neutral position, either by gravity or by their own stiffness. Wiechert (1613) makes the images of the two quartz filaments cross. Photographic registration is also easily possible in such a way by photographing the filament shadows, according to Bergwitz (173) and Wulf (1650). A comprehensive treatise on the electrometer, and instructions for use, are given by Berndt (176, 177).

In calibrating the emanation electroscope, the ionization current produced per unit volume can be calculated from the geometric and electrical dimensions of the ionization chamber, and from the capacity and sensitivity of the electrometer. Since a part of the α particles expelled by the disintegration of the atoms of emanation rebound from the walls of the ionization chamber before their energy is consumed in ionizing the gases, the ionization obtained in finite vessels will be too small; Duane-Laborde (362; 1100, p. 236) give a furmula for correcting this error in cylindrical chambers. Further, the ionization from transforma-

tion products formed after the introduction of the air containing emanation must be removed. With stronger ionization, a possible variation of the saturation value of the current must also be considered. Lester (945) has clearly set forth these conditions.

Recently, however, a relative method of calibrating by means of known, standard, radium solutions has been most generally used. In May, 1921, according to Ludewig (994, 995, 998), Freiberg planned to put the emanation measurement of spring water in the future on a basis of standard radium solutions of the Physikalisch-Technischen Reichsanstalt Berlin (1269). Becker (140, 141, 143) and Bothe (217) also treat of these relative methods of calibration.

The methods of measuring ionization used in the determination of emanation in fluids are employed also for the immediate determination of the emanation content of gases, for instance, of the soil gases. The first measurements of this kind were carried out by Elster and Geitel (386, 560, p. 55 *et seq.*). A similar apparatus is described by von dem Borne (208), and more recent reports of Kähler (791). In all these methods, the soil gases are introduced into the ionization chamber by means of a pump, where they are mixed with the air already contained therein. By continual pumping, the percentage of residual air is gradually reduced. Sometimes the ionization chamber is evacuated, and then allowed to suck up the air from the soil. Of late, however, according to a proposal of Lorenser (see also Link and Schober, 958*b*), the ionization chamber is provided with a movable flask which serves both as chamber and air pump to suck in the soil gases. An older arrangement of Ambronn (32) is similarly constructed. Small leaks in the arrangement sometimes permit atmospheric air to be drawn in along with the soil gases. Ambronn (32) later avoided this disadvantage when he, as shown in Fig. 40, sucked up the air from the well S, whose thickened middle part is securely caulked against wall pockets, the air being pushed up over a drying tube into the ionization chamber under slight excess pressure.[1] After several strokes of the pump t have rinsed the rest of the air in the vital part of the circuit through the filling cock a, with the de-aeration cock e open, the

[1] According to the same principle, for instance, one can also build fontaktometers when one constructs agitation vessels and ionization chamber as cylinders with movable flasks.

cock e is closed, and the piston K is driven down at each stroke while the ionization chamber J is being filled. The central electrode z is already negatively charged, so that the decomposition products are deposited in it. It can then be easily exchanged from time to time, to avoid contamination of the ionization chamber. When the chamber is filled, and the electrometer immediately read, comparable values are obtained for the emanation content of the soil gases, and yet measurements at each point can be completed in from 2 to 3 min. In moist weather

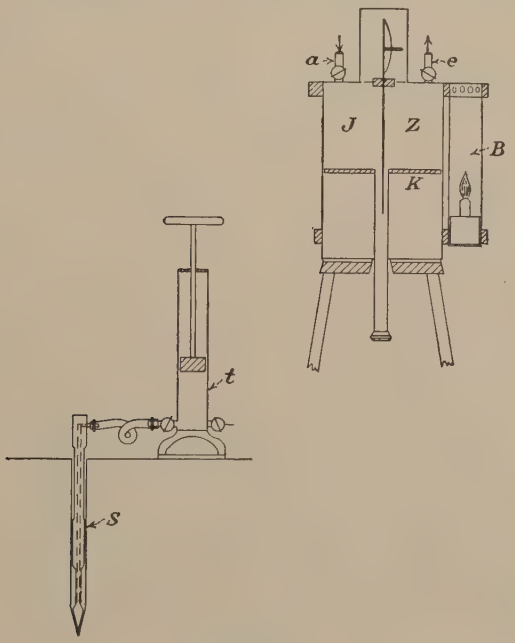

Fig. 40.

the apparatus can be heated somewhat by the benzine lamp B, or electrically. Dadourian (325) determines the emanation content of the soil gases by the wire activation method (see below), in which he hangs a negatively charged wire in a hole in the ground.

The emanation content of the soil gases is naturally dependent, not only on the radium content of the uppermost earth formations, but also upon the porespace, the size of the grains, and the dampness, as well as, according to Wright and Smith (1648), meteorological factors.

By diffusion, by the suction effects of barometric depression, of the wind, etc., the emanations formed continuously from the radioactive materials contained in the soil, as well as from the uppermost formations of the earth, go out into the air. Apparatus for measurement or registration of the quantities of emanation coming out of the soil, after discussion of their dependence upon meteorologic factors, are described in Ebert (374, 378), Endrös (392), and Wright and Smith (1648). Because of this diffusion into space, the emanation concentration up to 4 — 6 m. depth is less than the concentration corresponding to equilibrium with the radium content in the soil. This must likewise be taken carefully into consideration in the valuation of the emanation measurements of the soil gases for geological investigations. The dependence of the emanation content E upon the depth h below the surface of the earth can be indicated empirically by an exponential function of the form

$$E_h = E_\infty \cdot e^{-\frac{a}{h}}$$

where E_h indicates the emanation content at any depth. The constants E_∞ and a can be calculated from two measurements of the emanation content at different depths (for instance, 0.75 and 1.50 m.).

The emanations coming from the soil will be mixed with atmospheric air by the wind; and these form, according to present views, one of the most important sources of the weak ionization (conductivity) of the air, by which it exerts an essential influence on the distribution of electricity in the atmosphere. The determination of the emanation content of the atmospheric air forms, therefore, an important task for atmospheric electrical investigation. For details, reference may be made to published text books; for instance, by Chauveau (298), Mathias (1054), Mache and von Schweidler (1018), Kähler (792, 793) Müller-Pouillet, Lehrbuch der Physik (1148), von Schweidler (1414*a*) and von Schweidler and Kohlrausch (1415), Hess (716*a*), Schmidt (1398*b*), Negro (1157*a*).

The quantity of the emanation contained in the air can be determined in different ways. Methods of measurement of ionization described above can be used directly, or the emanation from measured quantities of air can be concentrated by passing it over cocoanut charcoal (1648), in a tube cooled by liquid air (see Satterly (1345) and Ashman (61)), or by strongly cooled

hydrocarbons. According to Elster and Geitel (385), the solid derivation products can be collected on a stretched wire carrying a high negative charge. This can be wound up and introduced into the ionization chamber of an electrometer to determine electrically the quantity of the precipitate (1100, p. 455, *et seq.*).

The electric condition of the atmosphere is further determined by the potential gradient and by the conductivity of the air. The potential gradient is determined by the difference of voltage between two so-called electrodes which are arranged at a perpendicular distance of 1 m. from one another; one of these is connected with the needle, the other with the case of the electrometer. The electrodes (see Benndorf (161, 163)), make the air in their immediate vicinity strongly conducting, according to Lutz (1005), Henning (702), by means of flames, according to Budig (270), Tuve and Huff (1553*a*), Mauchly (1057*c*), and others by means of a coating of ionium; or they depend upon the property of atomized water of assuming the potential of its environment (water jets, spurts, drop collectors), according to Lutz (1007), Budig (269). Consequently they take on the potential of the air stratum in which they are set up.

The conductivity of the air is determined by measuring the loss of electricity from a charged conductor (cylinder) which is connected with an electrometer. The loss is different for positive and negative charges (see Schering 1355*a*). On the other hand, according to Gerdien (532), if a measured quantity of air flows past the conductor, then from its charge the number of + or − ions per cubic centimeter can be calculated. From meteorologic and cosmic sources, furthermore, there are built up in space charges in which the ions of one sign preponderate and which, because of the relatively low conductivity of the air, adjust themselves very slowly, so long as they are not "shorted" by lightning and glow discharges (sheet lightning) (Gockel 564). On the origin, relations, and significance of such charges in atmospheric electricity, see Kähler and Dorno (796*a*), Obolensky (1190*a*), Benndorf (167*a*), Schmidt (1398*a*).

Benndorf (160, 164), Bergwitz (173), Rudge (1316), have reported on registration apparatus and erection of stations for measurements of atmospheric electricity. General descriptions are given by Gockel (556), Schweidler and Kohlrausch (1415), Mathias (1053), Baldit (92), Salles (1335*a*), Johnston (772*a*).

All magnitudes relating to atmospheric electricity as Bauer (130, 130*b*), Chree (304), Gockel (563, 564, 565*a*), Müns (1148*b*), Angenheister (50), Appleton (55), Fleming (457*a*), Mauchly (1057*a*) show, are in extraordinarily high degree dependent upon cosmic and meteorological factors. This must be very disturbingly noticeable in utilizing measurements of atmospheric electricity in geophysical prospecting.

A part of the radioactive materials found in the uppermost formations of the soil and suspended in the air emit very hard, penetrating rays whose measurement can be of importance for our task. A third constituent of these "penetrating rays" appears to arise from outside space, as Hess (716*a*, 716*b*) first clearly recognized, and Béhounek (152*a*), Büttner (281*a*), Hoffmann (734), Kolhörster (858*a*), Millikan (1105*a*), Millikan and Bowen (1105*b*), Millikan and Otis (1105*c*), and Ockenden (1190*c*) further confirmed. The detection of these penetrating rays results from measurement of the ionization of gas whose strong zinc walls are air-tight and 2 mm. thick. Such apparatus are described by Elster and Geitel (385), Wilson (1633), Wulf (1649), provided with photographic registration by Bergwitz (174) also, and recently further perfected by Kolhörster (854; 855, p. 29, *et seq.;* 856). In order to accelerate the measurements by strengthening the absorption, the pressure on the enclosed gases can be raised (Downey 359), and, according to Treleaven and McLennan (1548), (see also Broxon (252*a*), Lawson (922*b*), Merryman (1087*a*)), a heavy gas employed. The containing material is also of importance because of the escape of secondary γ-rays, according to Wright (1646). Kolhörster (858) covers the ionization chamber with tungsten foil and obtains double ionization on an opposite zinc foil. Comprehensive treatises on the measurement of penetrating radiations are given by Bergwitz (172), Braun (240), Ludewig (990); the most recent work is represented by Wigand (1620), and especially Kolhörster (855) in a monograph. On the surface of the earth, the penetrating radiation is preferably determined by the strength of the soil radiation. The radiation in space increases with height above the ground, until, according to Kolhörster (853; 855, p. 54 *et seq.*), at a height of 3,000 m. it has attained the normal earth radiation and at 6,000 m. height it has already reached the maximum value of earth radiation (see Chapman 293*a*, Mauchly 1057*b*). The radiation in air is already slight at the ground and

disappears almost entirely at great heights, since, according to Wigand (1621) and Bongards (203), the content in the air of radioactive material decreases quickly with the height. The individual radiation of the walls of the ionization chamber with good apparatus should be small and constant throughout. On daily or periodic variations of the penetrating radiation, there are reports by Hoffmann (733), Hess and Kofler (717), Kolhörster (855, p. 43), Eriksson (421*a*), Kolhörster and Salis (858*b*), Myssowsky and Tuwin (1150*a*).

The Use of Radioactive Measurements for Soil Prospecting.—The radioactive radiations, because of their strong absorption in the uppermost earth formations, yield, by direct measurement methods, only a minimum depth effect which has been variously, partially by Bogujawlenskij (197*a*), but never sufficiently, reviewed. They have, however, the advantage that very slight traces of radioactive materials can always be detected easily and quickly. Therefore, radioactive materials can make themselves noticeable by convection in waters and gas currents, and also at greater distances.

The immediate detection of uranium or other radium and thorium ores by means of radioactive measurements is such that along a cross-section or profile perpendicular to the supposed course of a seam, along a drift, or a shaft, or other ground test, immediately at the surface, or at slight, easily attainable depths, they can be tested by their radiations; or the radiations can be absorbed at point and place by means of ionization chambers placed on the ground; or, finally, they can be determined by their emanation content exhaled in soil gases. Von dem Borne (208) and Winnacker (1638) report on the same kind of investigations in uranium mining. Still, so far, the number of observation points is altogether too small.

A survey of the present known radium deposits is given by Petraschek (1226) and Krusch (876); Gockel (560, p. 40) assembles a great number of strongly radioactive minerals. Bothe (216) assumes as a lower limit to the possibility of economic exploitation a content of 10 mg. of radium per ton of ore. The radium and thorium content of the usual rock varies, as Gockel (557) shows, within wide limits. For fresh, unweathered rocks, Kolhörster (855, p. 11) gives the following table for the radium and thorium content per gram:

TABLE XIII

	Radium	Thorium
Acid rocks:		
Volcanic	$3.1 \cdot 10^{-12}$ g.	$2.5 \cdot 10^{-5}$ g.
Plutonic	$2.7 \cdot 10^{-12}$ g.	
Intermediate formations:		
Volcanic	$2.1 \cdot 10^{-12}$ g.	$1.7 \cdot 10^{-5}$ g.
Plutonic	$1.9 \cdot 10^{-12}$ g.	
Basic rocks:		
Volcanic	$1.1 \cdot 10^{-12}$ g.	$0.5 \cdot 10^{-5}$ g.
Plutonic	$0.9 \cdot 10^{-12}$ g.	
Sedimentary rocks:		
Clay	$1.5 \cdot 10^{-12}$ g.	$1.3 \cdot 10^{-5}$ g.
Sandstone	$1.4 \cdot 10^{-12}$ g.	$0.5 \cdot 10^{-5}$ g.
Lime and dolomite	$0.9 \cdot 10^{-12}$ g.	$< 0.1 \cdot 10^{-5}$ g.

Fletcher (459) cannot establish for limestone, sandstone, and slate a connection between their radium content and their geologic age. The average radium and thorium content of all rocks of the upper crustal formations of the earth is placed at some $2 \cdot 10^{-12}$ g/g. of radium, which corresponds approximately to $7 \cdot 10^{-6}$ g. of uranium, and $1 \cdot 10^{-5}$ g. per ton of thorium. Radium and thorium are contained, according to Waters (1582), (see also 560, p. 18), preeminently in individual accessory minerals of the rock mass, for instance, zircon, titanium minerals, apatite, allanite, anatase, rutile; and, therefore, their distribution fluctuates from case to case within the widest limits; compare also Geitel (527), Poole and Joly (1248), Sauer (1348*a*).

The inclusion of radioactive mineral fragments also shows itself in thin sections under the microscope by the formation of the so-called pleochroic halos. This phenomenon has been very thoroughly investigated and described by Mügge (1141, 1143) and Joly (782, 784) (see also van der Lingen (958*a*)). These halos are the cross-sections of spherical shells which surround the radioactive particles at the distance of the range of the α-rays of the different transformation materials of the radium and thorium in the kind of rock in question. From their radii, according to Joly and Fletcher (785) and Hövermann (745), conclusions can be drawn on the nature of the radiating materials, since the range of the α-particles is characteristic for each radioactive material. A reformation of the same pleochroic halos by

heat effects has been discussed by Gudden (591); reformation by irradiation is discussed by Weber (1588).

Goldschmidt (568) proposes to use the radioactive radiations of rare minerals for determining their composition, by spreading out the finely pulverized crystal in a very thin layer (some 0.09 mm.) on one electrode of an ionization chamber. Goldschmidt shows by numerous examples that this method may indicate the uranium or thorium content of many minerals with sufficient accuracy for the determination of the mineral.

In the investigation of a series of tests along borings, tunnels, galleries, the radiation varies considerably with the kind of formation. Such a series has been investigated by Joly (780, see also 560, p. 21) along the Gotthard tunnel, by Mache and Bamberger (1014) along the Tauern tunnel, Poole (1247) along the Lötschberg tunnel, Gockel and Wulf (566) along the Simplon tunnel, Fletcher (458) along the Trans-Andes tunnel, Büchner (267) in a well at Baarlo in Holland-Limburg, Eve and McIntosh (437) in a well at Beachville (Ontario), Joly in a well in Balfour, without being able to establish consistent relations with geologic formations. Smeeth and Watson (1455) found in the Kolar gold mine a constant radium content up to a depth of 1,000 m.

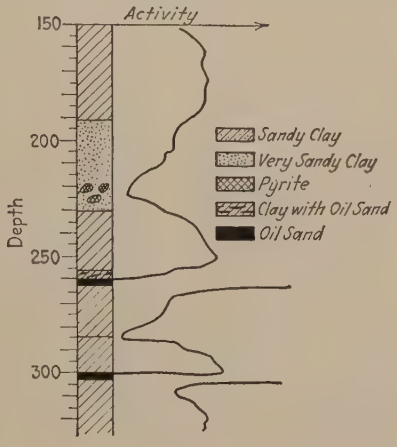

FIG. 41.

On the other hand, the measurements of von dem Borne (208) along the drifts of a uranium mine show the influence of the crossing of the drifts by seams bearing uranium ore in a thoroughly characteristic manner. Measurements were carried out by Ambronn (28, p. 45) on a series of samples from an oil well at Celle, using the radiation method. These have been shown diagrammatically in Fig. 41, beside the geologic section. The very high activities of the samples taken immediately below the oil horizon may be of practical interest. An entirely satisfactory explanation for this phenomenon has not been made. In this connection, mention may also be made of the radioactivity

profile of a well in the vicinity of the well-known gas seep at Neuengamme (Hamburg). The observations were made by Ambronn, and published by Heiland (671) and Ostermeyer (1206). The high radioactivity of petroleum (perhaps because of its great solubility for emanations) has been made the subject of various investigations; for instance, by Himstedt, (723), Fuji (492), Burton (278).

Hurinuzescu (755) shows that in Roumania some of the oils are strongly active, while the accompanying salt water shows very weak activity. The writings of Bogujawlenskij (197, 197*b*), indicate the same relation. According to Tscherepenkoff (1551*a*), the radioactivity of natural gases in the Baku district is not high (0.42 $\overline{\text{ME}}$ per liter). On the other hand, fantastic exaggerations of the application of radioactive measurements to soil investigation, as have been propagated by Vingerhoets (1564*a*) and Maurer (1057*d*), are, as Kauenhowen (801*a*) says, to be very definitely disregarded. Just as little confidence is deserved by the impossible apparatus of Pastor (radio emanator, etc.).

In the weathering of the solid rocks, part of the radioactive materials contained in them remain with the weathered mass. Viereck (1563) remarks that radium is only very slightly transported below by weathering, but that this process is more strongly marked for thorium. On the other hand, according to Kolhörster (855, p. 11), in the weathered crust the radium or thorium content should decrease more and more as the surface is approached, so that one might reckon for the weathered rock some 10 per cent of the value of Table XIII. Other investigators, however, found increase of the activity through weathering (560, p. 34 *et seq.*). The relations vary manifestly from case to case within wide limits. Nevertheless, in general, the transition from one kind of rock into another along the surface of the earth can still be recognized by easily observation of the radioactivity of the weathered products. Of particular significance are the measurements of Witte (1000, 1000*a*, 1639*a*) at Brambach, which have been confirmed and extended by Ambronn in investigations still unpublished. The radium and thorium content of the uppermost soil formations in the vicinity of Halle were investigated by Viol (1565). According to Brandes (236), the clay content of the soil should have a great influence on its emanation content.

In the year 1918, Ambronn (30) found, in crossing faults in the vicinity of Blanckenburg, a notable increase of the α-radiation of the soil. Often, as Fig. 42 shows, several maxima appear running parallel to one another. The observation has been confirmed by the author at many other places, and also by the investigations of Link and Schober (958*b*) in the vicinity of Wildbad. Also earth samples taken from some 10 cm. depth, whose rays have been investigated in the laboratory by the method of

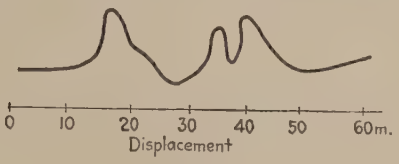

Fig. 42.

Elster and Geitel, afford corresponding curves. Besides faulting, the crossing of vein fissures makes itself noticeable in a similar manner. Figure 43 shows three profiles perpendicular to an iron-ore vein at Ilfield, in the Harz, at about 150 m. distance from one another. This vein forms the core of a high ridge dipping steeply on both sides, so that the topography could have influenced the results of the measurement, while along the crests

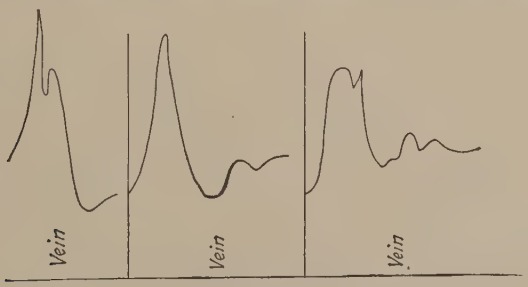

Fig. 43.

the dissociation products of the emanations contained in the air would have enriched themselves, according to the considerations of Salpeter (1337). The emanation of known lead veins in the Siegerland also has demonstrated clearly on a plane surface an increase of radiation from the soil. There is a report by Koenigsberger (839*b*) on the theoretical possibility of using radioactive investigations in potash mines for detecting the approach of drifts or borings to tectonic disturbances.

In the investigation of the emanation content of soil respiration, the magnitude of these effects appears very much greater, so that this method in its broader sense seems to be of great practical importance in the investigation of regions with sufficiently high activity of the ground water or the soil gases, to be used for medicinal purposes, and so in the search for radium emanation deposits (*e.g.*, Ambronn (33*d*), Bogujawlenskij (197*a*)), as well as for purely geological or technical questions.

The emanation content of the soil gases in its relation to geology has been discussed already by von dem Borne (208) with some examples. The statements in the literature are very contradictory. Watson and Pal (1583) have found the emanation content of the schists of the Kolar gold fields to be constant up to 1,200 m. depth. Brandes (236) believes that the emanation content of the soil gases is constant at 2 m. depth; this depth value, however, may be too small. Gube (589) studied the dependence of the emanation content of the soil gases upon the nature of the contiguous rocks in the vicinity of Halle, but found only slight differences. Satterly (1346, 1347, 1348) showed that the content of the soil gases in emanations capable of being sucked off depends upon its moisture content, and also varies notably in different areas. The greatest part of the emanations from the radium content of the rocks is retained in the rocks; only about $\frac{1}{10}$ becomes free, a proportion which may fluctuate strongly with locality. Gockel (555) treats of the importance of the permeability of the soil in itself, with which are connected the observations of relatively high emanation content of the soil over faults, since here, because of the disturbances, the permeability of the soil may be strongly increased up to a considerable depth. Ambronn (30) also sees a possibility of explanation in the easier circulation of solutions and gases on geologic disturbance surfaces, whereby radioactive materials could be transported and accumulated at the outcrop. According to Gockel (555) frost raises the emanation content of the soil through the effect of rising water. On account of the physiological effect of radioactive radiations and emanations on living organisms (*cf.*, for example, Falta and Schwarz (442), Lauter (921), Molisch (1130), Stoklasa and Penkawa (1487), Ludewig and Lorenser (999), Aschoff (60)), it is conceivable that increased radioactivity of the uppermost formations of the earth should exert an influence on the plant growth along faults. Observations in this direction,

however, have not been made up to the present. For therapeutic purposes, according to a proposal of Ambronn (33*d*), the highly active soil respiration from suitable disturbance zones, especially in radium-rich rock masses such as have been demonstrated at many places by Ludewig and Witte (1000*a*), Witte (1639*a*), Link and Schober (958*b*), as well as by the author in unpublished researches, can be sucked up by means of a system of tubes and either directly or after artificial enrichment (concentration), used for supplying emanatories (inhalation chambers) or for the preparation of highly active bath and drinking water. Likewise the emanation rich air of old mine drifts in Kreuznach is made usable in a skilful manner (60, p. 77). In general, according to Elster and Geitel (388), Schünemann (1410) and others, the ionization of the more or less stagnant air in caverns, cellars, shafts, etc., is especially high, because of the higher content of emanation which is diffused from the walls. Therefore, the soil gases in the formations over cavities lying near the surface of the earth can be relatively low in emanation content.

Emanation contained in the subsoil, according to Elster and Geitel (388), Joly and Smith (787), Smyth (1460), Ebert (375), and others, goes into the atmosphere by diffusion and earth breathing. It has also been proved by Sanderson (1340), Schmitt (1399), Joly (776), Knoche (817), Marten and Kähler (1047) and others, that for more extensive areas the emanation content of the atmospheric air runs parallel with the average content in radioactive substances of the rocks forming the subsoil.

On the other hand, the emanation content of the air over the sea, especially in the middle of great ocean surfaces, according to Runge (1330), Laub (920), Hewlett (719*a*), Hess (715), Kähler (796), Mauchly (1057), Thomson (1534*a*), is very slight, since the sea water was found to be almost free from emanations.

Simpson and Wright (1450) showed the great difference of the emanation content of the air over coastal regions with land and sea wind. On the contrary, according to Joly (784), the slowly accumulated sea mud is very active.

Bandl (93), who accidentally noticed that small local fogs always cling in the same place in the mountains, believed these condensations might be ascribed to the local ionization of the air through local emanation foci on tectonic lines. Knoche (816, 818) reports on some observations in the cordillera which

could indicate a connection between atmospheric electricity and stronger radioactive radiation from the surface in certain districts. But, according to Knoche (819), other explanations are also possible for excessive ionization, and according to von Traubenberg (1545) for the strong ionization of the air over volcanos. Chauveau (297) (see also Mathias (1054, p. 148)) finds an especially great conductivity of the air in the vicinity of hot springs. Whether luminous phenomena observed on trees by Layer (926) are related to radiations of the subsoil is still questionable, according to Süring (1503). On the other hand, it is remarkable that, according to Wilfer (1626), flashes of lightning seem to prefer certain strips in the country. These observations admit the possibility of finding local sources of radiation in the soil by means of aerial electric observations, measurements of the conductivity, the potential gradients, etc., and of bringing them into systematic connection with geologic phenomena. Gockel (562) also expresses the idea that the phenomena of atmospheric electricity can be better investigated regionally. The very great and irregular fluctuations, as well as the temporal variations, of the elements of atmospheric electricity produced, according to Huber (746), by meteorological conditions, and according to Mercanton (1085), Lees (930), Kähler (795), and von Schweidler (1414) by local influences on the stations, are worthy of notice. This will be possible only through exactly simultaneous measurements at adjacent points. In this connection, special reference should also be made to the work of Dorno (355*a*).

If the penetrating rays coming from the soil possess a higher value over certain surfaces or strips, then, on account of the considerable range of their effect, an effect would be observed in the conduction of atmospheric electricity, for instance, lightning paths. Gockel (561) observed that the penetrating radiation over crystalline rock with high radium content was greater than over cultivated soil. Especially high values for the penetrating radiation were found by Gockel and Wulf (566) in the Leone gneiss of the Simplon tunnel and on the rock massif of Cervin. Oberguggenberger (1190) has measured the penetrating radiation at numerous places in the vicinity of Innsbruck. Some measurements of penetrating radiations, carried out by the author with a Wulf's apparatus along profiles crossing faults which, according to page 127 were recognized by their increased α-ray activity,

have shown over these faults only a slight increase in the penetrating radiation.

The results, so important for balneology, of the systematic measurement of springs, especially healing springs, in regard to the radioactivity of their water and gas, cannot be gone into here. Their radioactive impurities doubtless arise from the formations through which the water flows, as Mache (1013*a*), Dienert and Guillard (350), Loisel (978), Mache and Meyer (1015), have demonstrated in special cases. Conversely, radioactive measurements at known subterranean spring paths can yield data on the nature of the formations through which the spring water flowed, or if the geologic structure of the region is known, indications are given as to the origin and the subterranean course of the spring. According to Streicher (1491), Ramsay (1270), Loisel (978), Ludewig and Witte (1000), Ludewig (992), the fluctuations in air pressure, in rainy or dry periods, which influence the productivity of the springs, as well as their combination from several sources of different origin, often have a very notable influence on the radioactivity of the spring water. Becker (142) made special note of the systematic differences between springs which contain only radium emanations and those in which radium salts also are dissolved. Whether the helium content of springs and natural gases is to be looked upon as a derivation product of radioactive materials is questionable, according to Sieveking and Lautenschläger (1447). Maureu and Lapape (1140*a*) treat of the possible connection between the radium content of mine gases and the radioactivity of coal. The natural gas wells utilized for helium production in the United States show only slight activity.

Comprehensive reports on spring activity, especially of healing springs, are found by Schiffner, Weidig, and Friederich (1362), Sommer (1464), Ludewig (997), Stephan (1480), Aschoff (60), Gockel (560, p. 90 *et seq.*).

Proposals have been made to detect the subterranean connection of trickling water or brooks with springs appearing at other places, by mixing each with radioactive materials and testing the spring water electrometrically for the appearance of these impurities; but the writer is unaware of any practical application of this idea.

The amounts of uranium, thorium, and their derivation products, helium and lead, in the different formations of the

crust of the earth may be used as keys to the most probable age of the rocks in question. Hahn (623*a*) treats of this in detail. With increasing age, the quantity of derivatives produced increases. Solid end products, especially lead, can generally be present also from other sources. This would make the age estimate too high. Since, however, the atomic weight of radium lead differs from that of the usual lead-isotope mixture, the percentage of radium lead in the rock in question can be estimated by exact atomic weight determination and a better age determination can be made. On the other hand, large quantities of the gaseous helium have already been diffused. Thus the apparent age would be diminished. Reports on such investigations are made by Lawson (924), Kirsch (809), Richards and Hall (1292*a*), and Holmes (736).

According to Lawson (923), with certain assumptions on the origin of the primal rock from the magma, the present quantity relations of thorium to uranium in the rocks can also be employed for derivation of the limiting values for their most probable age. From the special structure of the pleochroic halos (p. 124) according to Joly, Rutherford (786), and Gudden (591), the age of the radioactive minerals can also be determined.

On the basis of such considerations Bothe (216) gives the following comprehensive age determinations:

TABLE XIV

Formation	Probable age, years	Determined from
Oligocene	20,000,000	Helium content
Carboniferous	340,000,000	Lead content
Devonian	470,000,000	Maximum pleochroic halos
Pre-Cambrian	1,640,000,000	Lead content
Oldest known rocks	1,750,000,000	Helium content

These values also appear easily possible geologically.

By inversion of these methods, the geologic position of eruptive or intrusive masses can be reckoned through determination of their age by radioactive observations.

The heat production of the radioactive materials accompanying the disintegration of the rocks must make itself highly noticeable in the heat retentivity of the body of the earth. Very strongly radioactive rocks can be looked upon as local

heat sources, such as should be detected, according to Joly (775), in the St. Gotthard tunnel.

The average concentration of the radioactive materials in the earth's crust, however, appears puzzling. According to Elster and Geitel (389), it is so great that with similar concentration in the entire interior of the earth, the earth must, in the course of time, become ever hotter through the heat freed by their disintegration. Compton (313) thinks that perhaps, under the high pressure of the interior of the earth, the radioactive disintegration is retarded, and thereby the production of heat is diminished; Eve and Adams (436*a*) hold this as improbable. Becker (145), Joly (775, 779, 784*a*), Lotze (980*a*), and Strutt (1495) treat this problem in various researches. According to a more recent comprehensive report of Koenigsberger (831) it may be assumed as first established by Lord Rayleigh (1275*a*), that the radioactive materials are concentrated only in the uppermost crust. This assumption is also valid on other grounds. The heat effects which result from a series of different hypotheses on the distribution of the radioactive materials in the interior of the earth is discussed by Sokolow (1461) without attaining any definite results.

The interesting suggestions of Joly (784*b*), Müller (1145) are still to be considered with caution. He assumes periodic melting through the quantities of heat set free in the deepest formations of the solid earth's crust by the disintegration of the radioactive substances contained in them, and that when the mass becomes fluid, portions of it may wander in horizontal and vertical directions. Reference may also be made to the closely related works of Becker (146*a*) and Sonder (1465*a*), apparently in similar vein, and also to that of Lotze (980*a*).

CHAPTER V

ENERGY CURRENTS

We shall now treat of those methods of applied geophysics which investigate the propagation and transmission of currents of energy of different kinds, emanating from artificial or natural sources, in order to infer the character of the uppermost formations of the earth. We can differentiate here:

1. Methods Which Measure the Propagation of Electric Currents in the Subsoil.—In this connection there may also be discussed the electrodynamic methods (electric waves). The behavior of the subsoil under these two influences is determined by the electrical conductivity, by the dielectric constant, and, partially and indirectly, by the magnetic susceptibility of the soil. The treatment of the processes by which spontaneous electromotive forces are produced in the soil will be included in this group.

2. Methods Which Measure the Propagation of Elastic Waves in the Subsoil.—Here the elastic properties and the density of formations traversed by the seismic waves are determinative.

3. Methods Which Depend in the Uppermost Earth Formations on the Heat Currents Flowing from the Interior of the Earth into Space, while They Measure the Temperature Gradient within These Formations.—The individual segments of the subsoil influence the heat currents and thereby the temperature gradient because of the variations of heat conductivity. Its specific heat could be made use of only in fluctuations of the heat current. There will also be discussed the influence of heat producing deposits, as well as heat produced by connection due to the transportation of masses.

CHAPTER VI

ELECTRICAL METHODS OF PROSPECTING

The Extension of the Electric Current in a Conductor.—On the upper surface, or in the interior of a conducting mass, let an electric potential of $+e$ volts be applied at a, and a potential of $-e$ at b. Between the two electrodes a and b will then exist a potential difference of electromotive force $2e$, which produces a current i, flowing from a to b along individual lines of flow. Along each line of flow, the potential decreases from the value $+e$ at the point a to the value $-e$ at the point b. All points on the lines of flow which have the same potential difference Δe in comparison with the electrodes a and b, can be connected by a surface of equal potential, also called an equipotential surface. The potential theory teaches that such equipotential surfaces are perpendicular to the lines of flow. If the spatial distribution of the lines of flow has been determined in some manner, the corresponding equipotential surfaces are obtained as a system of surfaces at right angles to the direction of the lines of flow. With known equipotential surfaces, however, the current lines can be found from the fact that one can proceed from the one electrode always at right angles to the equipotential surfaces until one arrives at the other electrode. This is of great practical importance.

The current distribution in a conducting body adjusts itself to the shape of the body, according to the arrangement within the body of material of varying conductivity, and according to the position of the electrodes. The current distribution may be ascertained mathematically for a homogeneous body of simple shape. In the very complicated distribution of conductivity in natural soils, estimates and approximations must be depended on. The current distribution is always arranged so that a given potential difference between the electrodes corresponds to a maximum current strength. Each displacement of the line of flow to another position would lead to an increase in the total resistance between the electrodes, thus to a decrease

in current between them. In heterogeneous bodies where the electrical conductivity varies, the lines of flow follow the regions of high conductivity as far as possible, avoiding a long path through badly conducting regions.

More complicated relationships are formed if alternating current, instead of direct current, is introduced at the electrodes a and b. Then the peculiarities of the external circuit between the electrodes a and b, which are connected to the source of the current, can no longer be disregarded, but its electric properties and configuration must be taken into consideration. If the source of current in the external circuit (for instance, a dynamo) produces an electromotive force conforming to a sine curve, its momentary value will be given by the expression

$$e = E \sin \frac{2\pi}{T} t = E \sin \omega t,$$

in which E indicates the maximum value of this electromotive force, T the period in seconds, and t the moment of time, while the constant π is taken as -3.14159 . . . ω denotes the frequency of the circuit. The frequency of such a potential, and therefore also of the current produced by it, is

$$N = \frac{1}{T} = \frac{\omega}{2\pi}.$$

The angle φ, determined by the relation $\sin \varphi = 2\pi t/T$, for the present is designated as the phase of the potential e at the time t.

In consequence of the electrodynamic forces, set up by the alternation between the lines of flow of current distributed in the soil, there occurs a shift of the lines of flow between the two electrodes. This increases with the frequency of the alternating current used. The induction due, first, to the current flowing from the generator to the electrodes, and, second, to the system of lines of flow in the subsoil, acts in such a way that the lines of flow underground are displaced by electrodynamic forces set up between them and the current produced by the generator.

While, in a direct-current circuit, a current can flow only if the entire circuit is made up of conducting materials, the alternating current can pass over non-conducting material placed in the circuit between the conducting parts. Such currents are known as displacement currents. The impedance to an alternating current, due to such a non-conducting formation,

is proportional to its thickness, and is inversely proportional to its lateral extension (surface), the dielectric constant of the materials composing it (thus its capacity), and the frequency of the alternating current sent into the ground.

Thus, in a current circuit, aside from the source of the potential which produces the alternating potential, we have

$$e = E \sin \frac{2\pi t}{T} = E \sin \omega t$$

(Fig. 44); there are also present a self-induction L, a non-inductive resistance R, and a capacity C; then the momentary current strength at the time t will be

$$i = \frac{E}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} \sin (\omega t - \varphi),$$

where

$$\text{tang } \varphi = \frac{\omega L - \frac{1}{\omega C}}{R}.$$

The current strength of the soil, as may be recognized at once from the first of the two equations, does not go through its zero value, simultaneously with the fixed alternating potential, but earlier or later corresponding to the angle φ, which indicates the phase difference between e and i. The magnitude of the phase angle φ is apparent from the second equation.

If ωL is greater than $1/\omega C$, then tan φ is positive, lies between 0° and 90°; we have the current lagging behind the potential. If, on the other hand, ωL is smaller than $1/\omega C$, then tang φ will be negative, and variations in the current i precede corresponding variations in the potential e. L and C can be introduced into the circuit as self-induction coils and condensers, as in Fig. 44. However, each individual conductor influences the other as a capacity as well as an inductance. This must be especially considered in the results of electrical prospecting by means of alternating currents, since, in this case, such distributed self-inductances and capacities are often of greater magnitude than those in the external circuit. In the numerous treatises on electrical prospecting methods, these very important facts have been completely ignored up to the present, except by Ambronn (33, 33*i*, 33*k*, 33*l*). Later Heine (681*a*) and Zuschlag (1672) have

made note of these facts without applying them generally in theory and practice.

In alternating-current fields, the conception of the lines of flow of electrical current retains its significance only if momentary values of current are referred to. In prospecting by means of alternating currents, magnetic fields produced by the earth currents also attain practical importance. Each conductor through which current flows produces a magnetic field about itself. According to the elementary law of Laplace, a current

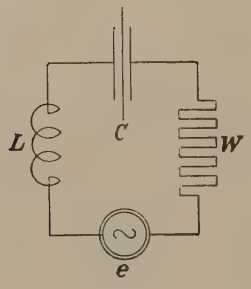

Fig. 44.

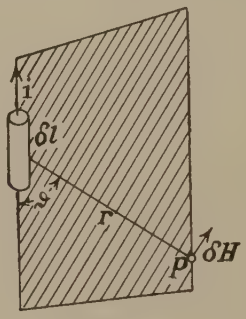

Fig. 45.

element of small cross-section and length δl (Fig. 45) carrying a current i produces a magnetic field of strength

$$\delta H = \frac{i\delta l}{r^2} \sin \vartheta$$

at a point P located a distance r from the current element and making an angle ϑ with it. The direction is perpendicular to the plane containing the current element and the point P.

The entire magnetic field at a point then is the sum of the individual effects of all current elements in the entire body through which the current flows. They are added vectorially, *i.e.*, taking into account the strength and direction of the individual effects. Conversely, however, in the measurement of the magnetic fields due to alternating currents in the soil, the electric lines cannot be individually established and separated from one another.[1]

[1] The designation of the lines in the maps given by Krahmann (Elbof method) (867*a*, pp. 16, 17), which are derived from induction space measurements, as "current lines" is, therefore, physically false and misleading. His designation given in the accompanying text as "lines of force" is also false.

For a straight wire of sufficient length through which the current flows, Biot-Savart's law is valid; consequently, the field strength H at the distance a from the wire axis is

$$H = \frac{2i}{a}.$$

The lines of force are drawn, as shown in Fig. 46, in circles around the wire (*cf.* also 376).

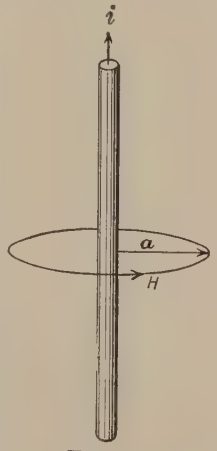

FIG. 46.

In current distributions, as they appear in electrical prospecting, all tubes of current (lines of flow) elements of the whole field, are additive vectorially. This rule holds also for alternating currents, as long as the size of the masses through which the current flows is not too great, and the period of the alternating current used is not too small. Otherwise, it must be considered that the electromagnetic effects propagate themselves from each current element with the speed of light.

Equipotential lines can be measured and represented on maps as continuous closed curves on the surface of the earth. In the measurement of the magnetic field due to the earth current, however, one obtains at each point of measurement the strength and direction of the alternating magnetic field, that is, the vectorial field. Thus, at each point of observation the vectorial arrows belong to singular lines of force and, therefore, may not be represented at the surface of the earth as closed uniform physical curves. Krahmann (867*a*) and Gella (531) completely survey these basic facts in the discussion of the magnetic field produced by ground currents. When the field distribution is not represented graphically, as by pins stuck in a map at the points concerned, for clear demonstration of the results of measurements, or, as in Fig. 67, only those lines dependent on the horizontal component of the magnetic force can be designated on the map. Such lines, as induction lines to characteristic curves, are, in contrast to the equipotential lines in general, not closed in themselves. These methods of representation are evidently possible only for a momentary field in which the magnetic force at every point possesses a definite direction and magnitude. For the complete representation of the magnetic

field in which, with alternating current in the ground, the magnetic force at every point describes a plane ellipse (see p. 171 *et seq.*), all six determinative parts of this vectoral ellipse must always be given; then, at the same time, all possible momentary fields are determined and can be derived by calculation or by diagrams (33*i*, *l*).

The Electrical Properties of Natural Rocks.—The electrical conductivity of the different constituents of the crust of the earth fluctuates within very wide limits. In the poorly conducting minerals, which form the great majority, the conductivity depends not only upon the basal substance, but often, in a decisive manner, upon its moisture content, and upon the materials (salts) dissolved in this (rock) moisture. If it is desired to determine the conductivity of a rock or ore sample in itself, without the influence of moisture, according to Löwy (983), the mineral is dried sufficiently if it is kept in a vacuum desiccator 10 to 15 hr.

The measurement of the electrical conductivity of mineral samples in the laboratory follows according to known methods, for example (851, p. 439 *et seq.*) on prisms or cubes which have been cut from the mineral in question oriented in the desired direction. For the estimation of the electrical properties of geologic masses in nature, however, such measurements have only a very limited value, namely, only in so far as the order of magnitude of its conductivity as a whole can be appraised from these measurements. In practice, it is much more important to study the *conductivity structure* of the mass in question, that is, the mixing and coalescing of the (electrically) different individual constituents within the mass. The conductivity often varies with temperature to a high degree. In crystallized minerals, the conductivity may be dependent upon the direction of the current with respect to the direction of the crystallographic axes (see Voigt (1569, p. 337 *et seq.*)). Since, however, in electrical prospecting only average values of the conductivity over great areas within which the individual crystals are heterogeneously intergrown come into consideration, the physical peculiarities of crystals can be overlooked. Measurements of the conductivity of rocks and minerals have been published by Braun (238), Dufet (363), Meyer (1097), d'Ossat (1205), Beijerinck (153), Bäckström (86, 87), Liebisch (956), Bädecker (87*a*), Löwy (983), Streintz (1492), Koenigsberger and Reichenheim

(843), Waterman (1581*a*), Ryschkewitsch (1335), Wilson and Herroun (1635), Kerr and Cabeen (805*a*), Krahmann (867*a*, p. 5). Table XV contains, in the first column of numbers, the electrical conductivity of a number of minerals as the reciprocal value of the resistance of a cubic centimeter in ohms (*cf.* also Landolt-Börnstein 904, Table 204).

The values given in the table for ores which are good conductors are valid for pieces which are dry and as uniformly free from cracks as possible. In the occurrences of ore in nature, the different ores are generally intergrown with one another with poorly conducting gangue minerals, as quartz, calcite, barite, and the like. This greatly reduces the conductivity of ores which are good conductors in themselves (conductivity structure, see above). The presence of water, according to Burbank (272), especially acidified water, bridges over these constituents in part. The conductivities in Table XV, therefore, afford only rough estimates of the distribution of conductivity in the interior of the earth. The enormous differences in the conductivity of the different minerals and other constituents of the soil, however, cannot be entirely accounted for by the phenomena mentioned above.

According to Koenigsberger (835), the electrical conductivity of coal is dependent of its gas content.

Conductivity measurements on masses in the soil itself in situ would be of especial importance. In different ways, Abraham, von Traubenberg and Pusch (5), as well as Gish (552, 553, 553*a*), and Rooney and Gish (1298) are trying to obtain more reliable average values. A further method is described from the measurement of the resistance between two electrodes of definite shape sunk into the earth, by Helmholtz (698, p. 311 *et seq.*), and Rüdenberg (1315). Wenner (1599) produced an electrical field in the soil between two field electrodes, and determined, for a known current strength, the potential difference between two electrodes put down between the two field electrodes. The calculation of the conductivity of the soil is possible in this manner only for entirely homogeneous subsoil (see p. 165 *et seq.*). Gish and Rooney (552, 553, 553*a*, 1298) extend this method to formations with parallel boundaries and always homogeneous conductivity. For rocks in which parallel formations of different conductivity (for instance, because of alternate soaking) alternate, as schists, laminated chalk, and

TABLE XV.—RESISTANCE AND DIELECTRIC CONSTANTS OF DIFFERENT MATERIALS

Material	Specific resistance ohm · cm^{-1}	Dielectric constant
Aluminum	$3.2 \cdot 10^{-6}$	
Amber	.....	2.8
Anhydrite	$>10^{11}$	6–7
Antimonite	$5 \cdot 10^{3}$	
Apatite	.....	8.5
Asphalt	.....	2.7
Barite	.....	9–11
Basalt	$2 \cdot 10^{9}$	12
Bornite	0.5	
Calcite	$5.5 \cdot 10^{14}$	8.2
Cassiterite	.....	24
Chalcopyrite	0.2	
Cinnabar	$2 \cdot 10^{9}$	
Coal, lignite	$>2 \cdot 10^{9}$	
Coal gas (retort-arc lamp coal)	$5 \cdot 10^{-3}$	
Coal anthracite	10^{17}	5.6–6.3
Copper	$1.7 \cdot 10^{-6}$	
Diabase	$2 \cdot 10^{8}$	
Diamond	$1 \cdot 10^{14}$	16.5
Diorite	$5 \cdot 10^{8}$	8.5
Dolomite	.....	7.3
Fluorite	.....	6.8
Gabbro	$1 \cdot 10^{6}$	
Galena	$26 \cdot 10^{-14}$	
Glass	$>10^{15}$	5–7
Gneiss	10^{8}–10^{11}	14
Granite	10^{9}–$>10^{11}$	8
Granulite	10^{7}–10^{11}	8
Graywacke	$2 \cdot 10^{10}$	9–10
Gypsum	.....	5.5
Hematite	$5 \cdot 10^{6}$–10^{9}	25
Hornstone	10^{6}–10^{10}	7–8
Hydrochloric acid:		
5 per cent	2.53	
10 per cent	1.59	
20 per cent	1.38	
Ice	.....	1.8
Iron	9–$15 \cdot 10^{-6}$	
Lead	$2.1 \cdot 10^{-5}$	
Limestone	$>10^{11}$	8–12
Limonite	$1 \cdot 10^{3}$	10–11
Magnesium sulphate in water:		
5 per cent	38.5	
10 per cent	24.4	
20 per cent	20.8	
Magnetite	0.6	
Malachite	.....	7.2
Marble	1–$100 \cdot 10^{9}$	8.5
Marcasite	1.0	
Melaphyre	$1 \cdot 10^{9}$	1.4
Mercury	$0.96 \cdot 10^{-4}$	
Mica	$9 \cdot 10^{15}$	5–8
Mica schist	$5 \cdot 10^{9}$	16

TABLE XV.—(*Continued*)

Material	Specific resistance ohm · cm^{-1}	Dielectric constant
Molybdenite	0.8–50	
Nickel	$1 \cdot 10^{-5}$	
Ozokerite	.....	2.2
Petroleum	.....	2
Phyllite	$>10^{9}$	12
Platinum	$1.1 \cdot 10^{-5}$	
Porcelain	.....	6.2
Porphyry	$1.5 \cdot 10^{9}$	13
Pyrite	$5 \cdot 10^{-2}$	
Pyrrhotite	$5 \cdot 10^{-2}$	
Quartz	10^{14}	4.0–4.7
Quartzite	$2 \cdot 10^{10}$	7
Sandstone	$5 \cdot 10^{9}$–$1 \cdot 10^{11}$	9–11
Salt, rock	10^{17}	5.6–6.3
Salt, cooking, in water:		
5 per cent	14.9	
10 per cent	8.25	
20 per cent	5.10	
Schist	2.10^{9}–10^{10}	7–16
Serpentine	$3 \cdot 10^{5}$	
Siderite	.....	7.4
Silver	$1.6 \cdot 10^{-6}$	
Sodium hydroxide:		
5 per cent	5.13	
10 per cent	3.24	
20 per cent	3.05	
Specular hematite	0.4	
Sphalerite	$1.5 \cdot 10^{8}$	7.8
Sulphur	$>10^{14}$	3.6–43
Sulphuric acid:		
5 per cent	4.78	
10 per cent	2.55	
20 per cent	1.53	
Syenite	10^{6}–$>10^{11}$	12
Sylvite	.....	4.9
Trachyte	$>10^{11}$	8.5
Wulframite	10^{7}	
Zinc	$6.1 \cdot 10^{-6}$	
Zircon	.....	8.6

the like, according to Schlumberger (1369) the conductivity is dependent of the direction in which the current penetrates the structure.

Table XV contains also a compilation of dielectric constants, submitted, according to Löwy (983), Graetz' Handbuch (578*a*, 1, p. 182), and Landolt-Börnstein's Tabellen (904, Table 194*a*). These data can naturally be looked upon only as approximate average values, and will serve only for corroboration.

The Measurement of the Currents Flowing in the Soil.—In electrical prospecting, there lies before us the task of interpreting

geologically the areal distribution of conductivity and dielectric constants in the subsoil. If an electric current flows in the soil from some source, then the form of the current lines in general will be determined by the distribution of conductivity in the soil.

The main task of electrical prospecting is thus to establish first the current distribution in the soil.

This distribution can be determined by measuring, by direct-current methods, the potential difference from a normal value at a sufficient number of points, and thus determining the position of the equipotential surfaces or lines. If alternating current is induced in the ground, then the plane ellipses of the potential vectors, in the subsoil or at the surface, must be measured quantitatively.

The distribution of the current lines, however, can be determined also from the distribution of the magnetic field due to earth currents. The measurement of this electromagnetic field forms, therefore, the second great group of electrical prospecting methods.

An appropriate combination of the two basic methods, however, will afford the most comprehensive basis for the derivation of the distribution of the electrical properties in the subsoil.

Direct measurement of the current flowing at a determined place in the ground is practically impossible. One could only follow, for instance, a proposal of Haber and Goldschmidt (620) of placing two unpolarized plane electrode plates parallel to one another as outside walls in an insulated frame and filling the intermediate space with the local soil so that the natural relations would be disturbed as little as possible. The potential difference between the two plates is then obtained by Ohm's law, from the magnitude of the current flowing between the plates and the known resistance of the material between the plates.

In practice, there are two methods specially applicable to the measurement of potential differences in the soil: namely, that involving Ohm's law, and the compensation method. In the first, the current produced by the potential difference to be determined must be measured in a connecting conductor of known resistance. This current must be taken from the current flowing in the soil, and care must be taken that this diverted current remains so small that it does not markedly disturb the natural current distribution in the soil (Petrowskij 1226*c*). In the compensation method, this back effect is avoided completely

by inserting an adjustable electromotive force in the external closed circuit, and so regulating it that it is equal and opposite to the potential difference to be determined. Under these conditions the current in the measuring circuit is reduced to zero, since the potentials impressed in it are equal and opposite (compensation method). With alternating currents, the phase of the earth current also must be considered; the compensating electromotive force must be equal to, and have the same frequency as, the potential difference in the soil which is to be measured, and must show a phase displacement of 180°. Only under these conditions does the current in the closed circuit always remain equal to zero (see Wenner (1599) and page 165). In the determination of the phase of a potential difference existing between two points in the ground, however, it is to be specially noted that the phase of a potential can be defined or determined only by its relation to a given normal phase, for instance, by its relation to the phase of the electromotive force of the alternating-current generator producing the ground current. This condition unfortunately is not always clearly recognized (for example, Zuschlag (1672)). Up to the present, the great majority of published works on prospecting by alternating currents takes no account whatever of these extraordinarily important phase relations, and must therefore be regarded as entirely obsolete with respect to the modern development of these methods.

In measuring the distribution of direct current in the soil, care must be taken to avoid the question of unknown electromotive forces set up by the electrodes (rods) by which the external measuring circuit is connected with the ground. At the boundary between the metallic parts of the electrodes and the electrolytic solutions in the soil, electromotive forces are set up which are dependent upon the chemical nature of these two contiguous components, upon the concentration of the electrolytes, and upon the temperature. The passage of the current through such a bounding formation is, therefore, connected with chemical processes. Thus, in general, there are produced further temporary changes in the electromotive force existing at the boundary. This phenomenon is known as polarization.

For the potential differences set up between different electrode materials and electrolytes, and for the polarization phenomena, refer, for instance, to the textbook of Nernst (1158) and Le Blanc

(927). There are reports by Skey (1452) and Wells (1598) on the electromotive forces between different ores and numerous electrolytes similar to the solutions in the soil. Simple metal plates or metal rods, therefore, cannot be used as pins in the investigation of the distribution of direct current in the soil. The older earth-current measurements which were made on telegraph lines with metal plates as grounds are very unreliable. Wild (1623), Schering (1356), Batelli (107), Bruchetti and Umani (253), Müller (1147), and others sought vainly to remove the influence of this disturbing polarization potential.

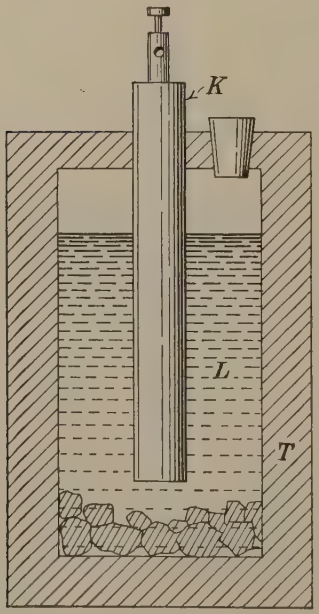

FIG. 47.

In direct-current measurements, one must use electrodes in which the chemical relations do not change with passage of the current (non-polarizable electrodes), for instance, a zinc plate in concentrated zinc sulphate solution. According to the direction of the current at the boundary, zinc goes into solution or is precipitated, the process being reversible, and the chemical relations do not change with the passage of current. Numerous models of such non-polarizable electrodes have been proposed and used. Thus Barus (102, p. 325 *et seq.*) used zinc plates, enclosed in a semipermeable animal membrane (gut) in concentrated $ZnSO_4$ solution. Schultze (1404) took amalgamated zinc plates in $ZnSO_4$, and also sought to use $CaSO_4$, $FeSO_4$, and HNO_3 as electrolytes; he further suggests that zinc be replaced by cadmium, for then the temperature coefficient of the electromotive force is especially small. Schlumberger (1367; 1369, p. 32 *et seq.*) also used non-polarizable electrodes in his researches, employing (Fig. 47) copper bars K in concentrated $CuSO_4$ solution L contained in a porous clay cell (see also Petrowskij (1226*b*)).

Since electromotive forces also appear between different electrolytes—though very small—Ambronn (410) has proposed that the cell containing the metal in a concentrated solution of

its salt should be inserted in a cell filled with a dilute solution of composition similar to the soil electrolyte. For general examples of normal electrodes, which can serve for the most exact measurements, see, for instance, Nernst (1158, p. 763), LeBlanc (927 p. 236 *et seq.*), Müller-Pouillet (1148, p. 575), Kohlrausch (851, p. 497).

Natural Earth Currents.—If two appropriate non-polarizable electrodes are buried in the soil at a great distance from one another, and are then connected by well-insulated wires through a sufficiently sensitive direct-current galvanometer, a deflection is generally observed. If w is the resistance of the connecting conductor in ohms, and i the current strength in amperes, then there exists between the two electrodes a potential difference $e = i \cdot w$ volts. If one divides the potential difference e by the distance between the two electrodes in kilometers, then the gradient of the potential in the direction of the line connecting the electrodes is obtained in volts per kilometer.

It may be assumed that these potential differences in the earth cause earth currents which flow in the direction of the potential gradient. In order to find this direction, the equipotential lines, which are perpendicular to the direction of current flow, are located.

In the scientific earth-current investigations at fixed stations, however, the potential gradient along two perpendicular or nearly perpendicular base lines is usually determined, and the direction of the maximum gradient, or earth current itself, is derived from these two components as their resultant. These methods also serve for the registration of the temporary changes of the potential gradient or of the earth current. However, it must be assumed that within the region in which conduction takes place, the distribution of the earth currents is normal, an assumption which should be checked continually.

Many reports have been published on methods of measuring currents with the help of telegraph lines, where the presence of such earth currents was first detected, and on the determination of the direction and magnitude of the maximum potential gradient from the components thus obtained. Barlow (97) [1849], in Derby, England, measured the earth currents on four telegraph lines converging from different directions, Blavier (194) on the telegraph lines running nearly perpendicular to one another, Paris-Lille and Paris-Juvisy. Records of the

earth currents have been kept since about 1880 on the telegraph lines from Berlin to Thorn and to Dresden, likewise nearly perpendicular to one another. Von Stephan (1479) and Weinstein (1595) have reported on this at length. In the Dutch East Indies, van Bemmelen (158) has carried out a comprehensive survey on a great number of telegraph lines running in different directions.

At a number of observatories, permanent conduction systems have been arranged in appropriately selected directions and with carefully prepared electrodes. Such stations have been established by Airy (13) in Greenwich, by Lamont (901) in Munich, by Wild (1623) in Pawlowsk, near St. Petersburg. In France, a station is found in Parc Saint Maur (1139); and in Spain an entirely modern arrangement in the Observatorio del Ebro (1132, 1554), at Tortosa. In the southern hemisphere a station is found at Watheroo (552) (Western Australia). A new station has been set up in Huancayo (Peru) by the Carnegie Institution (553*a*). At these stations the electrode distance generally amounts to some 1 to 3 km. (see Puig (1258*a* and 613*d*, p. 429, *et seq.*)).

Comprehensive descriptions of the arrangement of such stations are found in Battelli (106) and in Mathias (1054, p. 469 *et seq.*); Burbank (272) and Gish (553*b*) also refer to many points of special note in carrying out earth-current investigations.

In contrast with these permanent installations with electrodes built at greater distances from one another, Bachmetjew (81, 82), in his comprehensive measurements at many points in Bulgaria, used relatively short electrode distances of some 10 to 100 m. He used very special care in the preparation of non-polarizable electrodes. The star-shaped arrangement he used, of 8 to 16 outer electrodes about a central electrode, with galvanometer readings every half hour, has only answered the purpose of two perpendicular conductors, if one may consider that the current distribution and the electrical conductivity within the region of the station is not normal.

The potential difference between two electrodes placed on the surface of the earth consists of different components which possess, in part, the character of similar potentials changing slowly with time, and, in part, irregularly fluctuating potentials. The processes in a conductor grounded at both ends must, therefore, be more exactly analyzed.

If the electrodes are made of metal plates which behave differently electrochemically towards the subsoil, then there is formed

a galvanic element in which the soil plays the role of electrolyte. The potential difference between the electrode and the soil is dependent upon numerous meteorological factors (moisture, insulation, air pressure) and upon the duration and direction of the passage of current. The currents produced through these causes are known as electrode currents. By employment of non-polarizable electrodes built exactly alike and of similar material, the electrode currents themselves, and, even more, their fluctuations, can be made practically negligible. The electromotive force of the electrode currents is practically independent of the distance between the electrodes, so that their influence on the length of the circuit will be very slight.

Further, the formations in which the two electrodes are imbedded may contain different salt solutions, in different concentrations, and thus form a concentration series ((1158, p. 784 *et seq.*), (927, p. 176 *et seq.*), (1148, p. 570 *et seq.*)) which produces a potential difference. The two electrodes are then separated from each other by a zone within which the potential changes. This phenomenon makes itself especially noticeable if one electrode lies within an ore body which produces an electrochemical potential difference between it and the formations containing it, see Fox (481), Becquerel (149), Schlumberger (1369), Hummel (750).

The singular observation of Milne (1110), that in Japan within from 5 to 50 m. of some hot springs there were found potential differences up to 0.5 and 0.6 volt, which, on account of their magnitude, can scarcely be of a thermoelectrical nature, perhaps belongs here. It is desirable that the potential distribution about other hot springs also should be systematically investigated.

In mountain regions the current almost always flows up hill in the conductors, that is, the higher electrode is charged negatively with respect to the lower. Numerous examples of this phenomenon are found in Bachmetjew (81), in Bulgaria, Baumgartner (135), on the Vienna-Graz telegraph line, as well as in Brunhes (256, 257), Brunhes and David (261), Brunhes and Marchand (1043), who reported the measurements on the Pic du Midi and the Pui de Dôme. Similar phenomena on Ben Nevis have been observed by Dickson (347) as long as the summit was clear; if it was cloud-covered, however, the direction of the earth current was reversed. Amerigo (34) observed similar currents on Monte Rosa. The most recent measurements of

Oberguggenberger (1189) in the vicinity of Innsbruck likewise show in almost all cases a flow of the earth current from valley to mountain. Koenigsberger and Hecker (841) found the same thing at Gonzen in Switzerland. Still greater potential differences are found between points on the surface of the earth and in the depths of a potash shaft at Wesel. Corresponding observations were made by Oberguggenberger (1189) on a drift near Innsbruck, while Brunhes (257) had also noticed potential differences between electrodes placed at different depths in a mine. On Vesuvius, after years of earth-current measurements by Palmieri (1209), no proportionate potential difference of the upper electrode with respect to the lower one was to be detected (see also Capperera (283*a*)). The potentials vary much more strongly, obviously under the influence of the volcanic activity of the mountain, as well as the numerous geophysical and meteorological phenomena accompanying it, which Stäger (1468) also investigated.

The earth currents, obviously flowing in the crust of the earth from below to above, are analogous to the vertical currents detected in the atmosphere (see, for instance, Lutz (1006), Dechevrens (337*a*), Maurain, Salles and Gibault (1062*a*)). The earth-surface potential gradients are analogous to the vertical potential gradients measured in the air due to its conductivity. On the soil itself, the potential gradient amounts, according to place and time of year, to some 10 to 100 volts per meter, but decreases with height (see also Idrac, 762*a*). The electrical field in the soil is determined, for example, by Ray (1274*a*), Rodebush and Fiock (1295*b*) Ramsauer (1269*a*), Schlomka (1366*a*). On the other hand, the conductivity of the air, due to its ionization and the mobility of the ions, shows an increase with height above the surface of the earth, according to the investigations of Gockel (559), Simpson (1449), Everling and Wigand (440), Wigand (1619), Swann (1504), Benndorf (167), Sanford (1343), so that relations between these phenomena have not yet been completely determined. It is possible that investigations over greater regions with a close net of stations, which are completely lacking at present, would yield results which could be employed for practical geological purposes. A direct method for the determination of the vertical electric currents in the air was used by Simpson (1448) at Simla when he exposed an insulated surface, some 17 sq. m. in area, to the open air, close to the soil, cor-

responding to part of the natural surface of the earth, and measured the electric resistance of this surface. Corresponding methods using smaller gathering surfaces are described by Wilson (1633), Ramsauer (1269*a*), Pacini (1206*a*).

Another method for determining the vertical electric currents, which, however, is now usable only for greater regions, results from the quantitative analysis of the earth's magnetic field on the basis of the Gauss potential theory. Bauer (126) shows that while the greater part of the earth's magnetic field on the surface of the earth, namely, about 97 per cent, possesses a potential, the remaining 3 per cent possesses no potential. This potentialless portion must be produced, according to the present views, by electrical currents which flow perpendicularly to the surface of the earth. The current strength i per square kilometer within a surface F will be found from the expression $4\pi F \cdot i = \int H \cdot \cos Dds$, which indicates the work which will be performed if a unit magnetic pole is led around the surface element F, while H indicates the horizontal intensity, D the angle between it and the boundary line of the surface F, and, finally, ds the linear element of this bounding curve (*cf.* Nippoldt, 1177, p. 37 *et seq.*). Numerous calculations of the vertical currrent have been made on this basis by Bezold (182), Rücker (1310), Maurain and de Madinhac (1061), Bauer (112, 124, 132), Schmidt (1390*a*), and in a somewhat different form also by Peters (1222). According to the most recent investigations by Bauer, which are based especially on magnetic measurements over the entire earth organized by the Carnegie Institution, the surface of the earth can be divided by the two circles of latitude 45° north and 45° south of the equator into two polar caps and an equatorial zone. This arrangement shows for the equatorial zone an influx of positive electricity 354×10^4 amp. in magnitude, while within the northern or southern polar caps 194×10^4 amp. or 160×10^4 amp. flows off again. Within the earth itself this current must be equalized by a component of the earth current directed toward the polar caps. Compare also Benndorf (167).

However, if the values derived magnetically in this way, are compared with those which have been obtained from the aerial electrical measurements and with the present meager and scattered data on vertical earth currents in the earth, there result the greatest, and at present entirely unexplainable, contradictions conceivable: the currents calculated from magnetic data

amount to some hundredths amperes per square kilometer, the aerial electrical currents some thousandths amperes per square kilometer, while the least value of the vertical earth current submitted up to the present time is about 1 ampere per square kilometer. The publications of von Schweidler (1414*a*), Benndorf (167), Swann (1504), and Seeliger (1427) deal exclusively with these discrepancies, without, however, offering a solution.

Besides the earth-current components with preponderantly direct-current character, a great number of other causes influence the structure of the earth currents. These influences call forth electromotive forces variable in time whose periodicity fluctuates within the widest boundaries. Chapman and Whitehead (295) tried to draw from these phenomena conclusions on the general constitution of the earth as a whole. For the purpose of practical prospecting, these fluctuating components in the earth current, still appear to have no practical importance whatever. It may not, however, be hopeless to use the magnetic effect of these fluctuating constituents of the earth current, especially those of short period, for the study of the areal distribution of the electrical conductivity of the upper earth formations. Ambronn (404) assumes that the earth currents circulating in the upper earth crust can be notably influenced for practical purposes in their distribution, according to strength and direction, by the geologic structure of these formations.

An annual periodicity of the earth-current phenomena corresponds to the revolution of the earth around the sun (1595). The daily period is very strongly marked, and is discussed in its relation to terrestrial magnetic processes by Steiner (1476), Nippoldt (1174), Weinstein (1595), Bauer (127), Chapman and Whitehead (296), Gish (553, 553*c*), and others. Bachmetjew (82, 83, 84) shows a dependence of the earth current upon daily fluctuations of the ground-water level, in which he refers to the current currents discovered by Quincke (1264) and worked out by von Helmholtz (697) and Dorn (355), which are produced by currents of liquids, for instance, ground water, through porous formations. This phenomenon could perhaps be connected with the dependence of the earth currents in conductors or cables upon the tides observed by Graves (581), Sharp (1432), and Dechevrens (337), in which, furthermore, a monthly period of the earth current, treated by Sanford (1341), is presented. There is a report by Hamer (628) that earth currents can be produced by thermo-

electric forces excited by alternate heating and cooling of the surface of the earth in its rotation. Through the agency of atmospheric electricity or terrestrial magnetism, according to Sanford (1341, 1342), static charging of adjacent heavenly bodies may perhaps have some influence on the temporary paths of the earth current.

Under the action of the sun's rays in the highest air strata above the earth, rotating electrical-current vortices are formed, which, according to Nippoldt (1148, p. 1365) affect the daily fluctuations of the earth's magnetic force, and, according to Blavier (193), Trowbridge (1549), Schmidt (1389), stimulate earth currents simultaneously through induction. The fluctuations of the conductivity and the potential gradients in the atmosphere disturb the distribution of the atmospheric electric currents, and can, therefore, according to Landerer (902), Gockel (558), and others, induce earth currents in order to restore again the electrical equilibrium on the surface of the earth. Changes in distribution and magnitude of space charges in the atmosphere can, according to Daunderer (332) and Kähler (794, 795), produce earth currents through induction. Notable disturbances of earth currents were observed by A. Ludewig (988) and Brandes (237) in the adjustment of such space charges in the form of lightning. Disturbances in the telephone, as Conrad (315) describes, are explained by earth-current disturbances due to silent discharges (St. Elmo's fire).

Although these fluctuations of the earth current of long periods possess only slight importance in geophysical prospecting, they should still be borne in mind in order to correct observed earth currents (or measured potential fields) for their influence, and in order to be able to derive average values.

The first observations on earth currents, however, were made, not on these relatively weak continuous currents, whose magnitude fluctuates only very slowly, but on the very much stronger, severe, and irregular sudden current fluctuations in long telegraph lines, which temporarily excluded their normal use. It was soon recognized that such sudden earth currents appeared simultaneously with strong polar lights and strong magnetic storms.

Other corresponding phenomena also depend upon the influence of the central body of our solar system on the magnetic processes of the earth, *e.g.*, the sudden fluctuations of the earth

currents upon the periodicity of the activity of the sun. The question of the causal connection between solar activity, polar light, earth magnetism, and earth currents may be left entirely open here, since the kind and the direction of this connection have not yet been clearly established. It also possesses no essential importance for our purposes. For general information on this question, the works of the following may be referred to: Barlow (97), Thomson (1531), Airy (14, 15), Shida (1439), Lemström (940), Steiner (1476), Lamont (901), Nippoldt (1174, 1177, p. 104 *et seq.*), Bosler (214), Mathias (1054, p. 480 *et seq.*), Bauer (125, 127), Stenquist (1478*a*), Peters (1222*a*), Peters and Ennis (1222*b*).

Sudden current fluctuations in wires grounded at both ends can arise in different ways. There can actually appear along the surface of the earth high-potential differences which have been observed in strong earth-current storms up to 1 to 2 volts per kilometer. Their origins have not been entirely explained. Possibly strong electric currents could have been induced in the crust of the earth by induction effects of magnetic storms. In this case, in the first approximation, the potential difference between the electrodes would be proportional to their distance.

Such induction effects, however, could be exerted directly on the conducting loop, which is formed by the conducting wire between the two electrodes, and the return circuit in the soil. Then the rate of change of the number of magnetic lines of force which penetrate the surface bounded by this loop would determine the induced electromotive forces and the current strength. At what depth and with what cross-sectional distribution this return circuit is to be considered has not yet been investigated. Perhaps this problem could be attacked in practice by introducing into the wire, artificially grounded on both ends, another coil of greater area, so that the electromotive force produced in it through the changes in the earth's magnetic field would oppose that induced in the earth loop. Through change of the active area of the coil, or through change of its coupling with the earth loop, the part of the so-called earth current which is produced by the immediate magnetic induction in it, as well as the area of the earth coil, could be measured. Also the phase differences of earth current components caused perhaps, in different ways by the same origin, could be determined and applied to the explanation of the phenomenon. Furthermore, by considering the length

of the earth conductor, the average depth of the return current in the crust of the earth could be calculated. It does not appear unreasonable that in this way one would also obtain information about the distribution of conductivity down to considerable depths in the earth's crust. In conductors of different length, this induced electromotive force would be proportional to a higher power of its length, as the return current may lie deeper, with electrodes farther distant from one another. On electrodynamic grounds, the depth of these return currents must, under otherwise similar conditions, be dependent upon the frequency of the earth current.

Since atmospheric conduction and cables may be equivalent to artificial connection between the electrodes, the return current must be fairly deep under the surface of the earth.

Walker (1576) observed earth currents on different sections of a telegraph line, of very different strength, and sought to connect these differences with the geologic structure of the subsoil. Systematic investigations on this question are very much to be desired, at any rate in the interest of practical research.

Likewise the question of whether seismic phenomena can be connected with earth currents has not been fully explained. The thought cannot be rejected that, through the ruptures and displacements which occur in connection with earthquakes, electric currents can be produced and the spatial distribution of the existing earth-current system can be disturbed. Observations and investigations on this question are furnished by Serpieri (1431), Milne (1106, 1109, 1110), without a decisive conclusion.

The artificial disturbances of earth current, due to electric railways and high tension lines, often cause, according to Ellis (384), Rücker (1312), Girousse (551), extraordinary disturbances in the observations. They need no further discussion here, however.

Electrochemical Phenomena in Deposits of Different Kinds.— In the first half of the nineteenth century, Fox (476), in the copper and lead mines of Cornwall, determined for the first time electrical-potential differences between different parts of the ore. In many different investigations, Fox (476, 482) showed in numerous ore occurrences that an electric current flowed between metal plates connected by an insulated wire and a galvanometer and pressed on two ore-bearing deposits. The direction and

strength of this current varied according to the dimensions of the component parts, but were remarkably constant with time. Such potential differences seem to occur especially in copper veins, and to a lesser degree in lead mines (481). In a mine which works as a bed bearing a lead ore, no current is shown (476). Fox (476) set up a series of potentials between different ores and Zn, Cu, Fe, and Pb in sea water and in diluted hydrochloric acid, after Poggendorf (1243) and Marianini (1045) had compared the electromotive force of ores with that of different metals. Meanwhile the measurements were repeated by Erhard (421) with improved apparatus. Besides the deflection of the galvanometer needle, these currents also showed electrochemical effects according to Fox (482).

These investigations were further confirmed by Petheric (1225). Bennets (168) believed he could recognize that the electric effect increased with the copper content. Henwood (708) refers to the fact that only ore lodes, but not the gangue rock, may serve as electrode connections, and confirms in other quarries the observations of Fox. Henwood (708) gives a comprehensive collection of the literature which has appeared up to the present, as well as the individual observations. In Germany, Reich (1282) confirms the results obtained by the English investigators, and treats of their efficiency in searching for unknown ore deposits (1283), while von Strombeck (1494) was not able to establish such currents in the Werlau and Holzappel veins. In other mines, on the contrary, Hunt and Philipps (753), and Hunt alone (752), detected potential differences. Maggi (1027) treats of the geognostic value of electric currents. Cotta (320), in his vein studies, assembled the greatest part of the literature on the electrical activity in ore seams that had originated up to that time. The cause of the more definite detection of potential differences in ore seams was immediately traced by Fox (476) to electrolytic processes in the vein formation, while Henwood (708) added the opinion that it was a question of thermoelectric effects. The electrochemical theory has been successfully represented by Becquerel (149, 150, 151), De la Rive (344), and Dufour (366).

After this first attack, the electric investigation on ore deposits remained at a standstill. The apparatus given by Fox could yield serviceable results only under especially favorable conditions, and Barus (102) believes that the publication of negative

or doubtful results observed in further researches was not encouraging.

These observations on the electric activity of certain ore deposits at the same time gave an inducement for the advancing of an electrochemical theory for the origin and the metamorphic phenomena in ore veins. Fox himself (479) has already treated this question. He tested the structure of artificial crystals by electrical means (480) and believed in the origin of entire ore veins (479) through electrochemical processes under the effect of earth currents. Becquerel (147, 148) also applied himself in a very extensive way to these problems. Von Fritsch (487*a*) and Hunt (751) also report on their investigations relative to the influence of electric currents in the formation of minerals and ore bodies.

With modern equipment, the extensive and careful investigations of Barus (102) were made of the electrical phenomena in the Comstock Lode and in the Washoe and Eureka districts. Carefully constructed non-polarizable electrodes were used to decrease the potential at the measuring points. The potential distribution in the interior of the drifts was explored along extended profiles. The resistance of the circuit loops, as already carried out by Erhard (420), was exactly determined, and the potential differences between the measuring points was measured. On the surface of the earth also, electric profiles were measured and potential differences were established. The properties of the equipotential surfaces of the electric current excited by the ore body have already been treated there.

Through the works of Barus (103), Buehler and Gotteschalk (271), Wentworth (1600) (*cf.* also Matsubara (1055)), and especially through the extensive physical investigations of Wells (1598), an unobjectionable explanation has been found for the origin of spontaneous potential differences in ore deposits and the electric earth currents produced by these in their vicinity. It may be demonstrated that in ore bodies whose parts border on chemically different soil solutions, electric currents arise, whereby chemical processes take place simultaneously at the contact surfaces. The strongest electrical effects were attained if oxidizing and reducing solutions could work on different bounding surfaces of a conducting ore body. Oxidizing solutions are most likely to be found in the uppermost ground-water formations, where the carbonic acid material, penetrating with the precipi-

tation, caused the oxidation of the ore. Reducing solutions are rather to be expected at greater depths. The ore body (Fig. 48), under such circumstances, will appear positive above, and negative below, toward the bounding solutions. A current in the vicinity of the ore body, from above to below, corresponds to this condition. At the surface of the earth over the ore body, there will be formed a region with negative potential towards distant surroundings.

The practice of investigating active ore bodies on the basis of these electric phenomena by means of suitable apparatus has been especially developed by Schlumberger (1368; 1369, p. 73 *et seq.*) and his students. Application of this method to the search for various deposits of pyrite, nickel, gold, silver, and

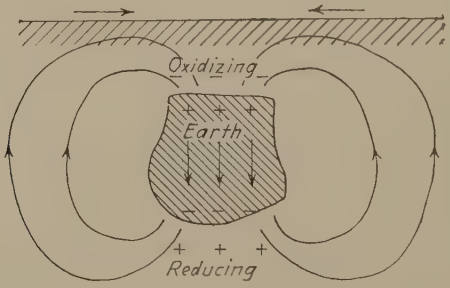

FIG. 48.

cobalt ores have been described by Schlumberger himself (1370), as well as Kelly (803) and Emmons (391). The last named also showed that conducting anthracite deposits could be electrochemically active, obviously after the manner of a gaseous element. Theoretical expositions and examples of the appearance of spontaneous earth currents in the vicinity of ore bodies are given also by Petrowskij (1226*a*). With especial consideration of the secondary deposits, Hummel (750) treats of the spontaneous electrical activity in ore deposits.

The carrying out of the measurement of the potential field of such spontaneous ore currents is relatively simple. Two exactly similarly constructed non-polarizable electrodes are connected with each other through a very sensitive galvanometer. One of these electrodes is placed at a point P on the surface of the earth as the fixed electrode (Fig. 49), and by moving the other electrode along a line $q - q$ a point Q is found on the surface of the earth

which exhibits the same potential as the fixed point. This is recognized by zero current in the galvanometer G between the electrodes. The point Q thus found then lies on the same equipotential surface as P. If the distance between the fixed and the movable electrodes becomes too great, the fixed electrode P is brought along an equipotential surface until closure is obtained. The failure to close gives at once a measure of the accuracy of measurement. Work in a new adjacent region is begun when the initial point P is moved a corresponding distance perpendicularly to the previously measured equipotential line.

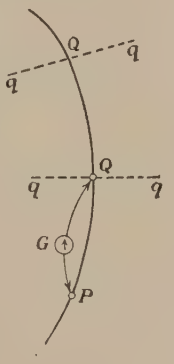

FIG. 49.

Another method consists in measuring the absolute potential difference of a sufficient number of points distributed over the whole region to be investigated, compared with a fixed normal point and then drawing in, by interpolation, on a map-like diagram, the lines of similar potential (see Fig. 54).

In investigations with the help of such natural earth currents, it is to be observed that their appearance presupposes a sufficient moistening of the subsoil. Furthermore the strength of the effect is dependent upon the magnitude of the surface of the ore on which the investigation is made, but not upon the amount

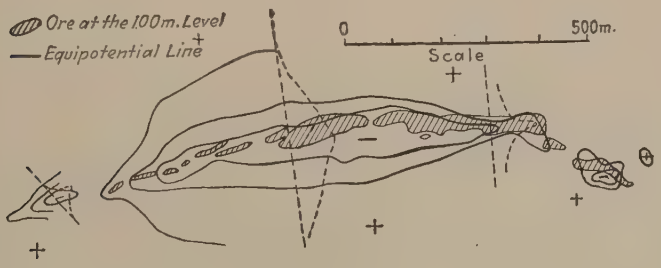

FIG. 50.

of ore itself. Impregnations with greater total surface of the ore-body have much stronger effect than large compact masses of ore. In this case the physical conditions are in strong opposition to the economic purposes of the investigation.

The equipotential lines (or surfaces) surround the ore body; the region above it is, in general, negative toward the distant

surroundings, though secondary positive-disturbance regions also occur. Figure 50 shows such equipotential lines on the pyrite occurrence of Saint-Bel, according to Schlumberger (1369, p. 76). The shaded region gives the ore deposit in section at a depth of about 100 m. below the surface of the earth. The dotted profiles show the quantitative changes of the potential in the transverse direction across the vein. Petrowskij (1226*b*) also reports on such measurements.

Earth Investigations by Means of Artificially Excited Electric Currents.—In addition to the foregoing methods of measuring the natural potential fields, there are the methods of measuring electric-current distribution artificially produced in the soil.

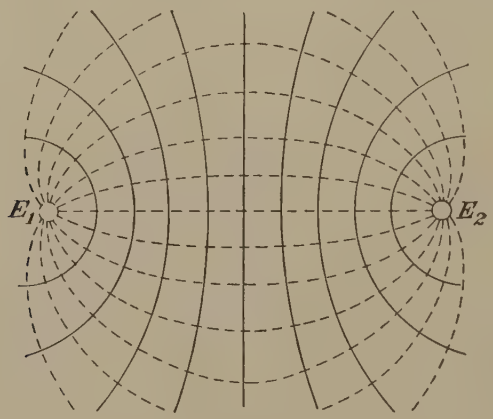

FIG. 51.

These currents may be produced by direct or alternating electromotive force sources for the delineation of especially well or especially poorly conducting deposits in the subsoil.

The manner in which the electrical current field is produced in the subsoil, and the geometric form which is given it, are of especial importance for practical success, in the use of direct as well as of alternating current. In the alternating-current methods, on account of the presence of induction and capacity phenomena, the position of the conductors connecting the alternating-current generator to the field electrodes, as well as the frequency of the current, influence the current distribution in the subsoil.

Schlumberger (1367, 1369, p. 10 *et seq.*) uses point electrodes; the lines of force connecting them are distorted by the subter-

ranean object sought. Figure 51 shows schematically the form of the equipotential and current lines between such point-electrodes E_1 and E_2 in level country over an electrically homogeneous subsoil. Figure 52 shows the same in a region disturbed by the conducting vein A-A. For the sketching of such schematic current and equipotential pictures in the laboratory, an investigation trough, such as conducted and described by Ambronn (30) (see also Zschaage (1669) and Sundberg (1500*c*)) is well adapted.

In surveys in the country, current is supplied to the soil through metal spears stamped down into the earth or buried plates (zinc, sheet iron coated with zinc or tin). In order to

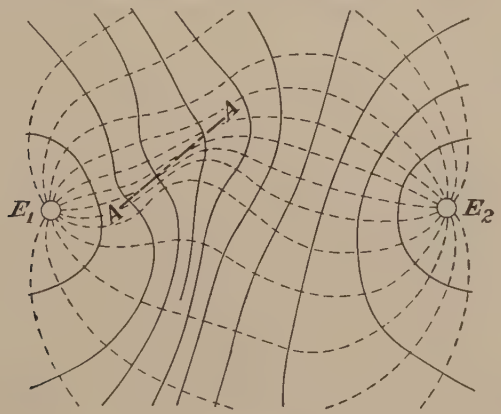

FIG. 52.

lessen the contact resistance, one can distribute a great number of such electrodes in a region small compared to the electrode distance. In dry soil it is recommended that the electrodes be "watered" with water in which a hygroscopic salt, for instance, calcium chloride, copper sulphate, and the like, has been dissolved. What practical advantage the field electrodes, according to Piepmeier (1237) should possess, is not perceptible.

When, with the use of point electrodes, the distortion brought about by the desired deposition in the subsoil is not sufficiently noticeable, Lundberg and Nathorst (1001, 1002, 1152) (see also Lundberg and Royers (1003)) propose to prepare and lay in straight lines parallel to one another, two electrodes of polished metal cables buried in the soil, or a series of regularly distributed electrodes, connected with one another but point-formed in

themselves. Then within the intermediate region the current lines would form parallel line systems in which the disturbances should be clearly observable. Ambronn (415) proposed to arrange such polished cables or connected point electrodes, connected to one another, on both sides of the region under investigation in surface-like distribution, in order to make the current distribution in the soil of similar form. Petrowskij (1226*b*) also discusses a number of different electrode forms exhaustively.

In these kinds of electrodes, however, the individual grounding places or the unit lengths of buried cable show entirely different contact resistances toward the soil, so that already along the electrode positions themselves the field in the soil will be very strongly disturbed—and in an entirely uncontrollable manner. The beautiful disclosures obtained in the Swedish ore district result in spite of the line electrodes, since the enormously large and extensive ore bodies which are sought are covered only by a few dozen meters of poorly conducting formations.

The electrical distribution would be more favorable if one, according to Ambronn, connected the individual spatially distributed grounding points or regionally assembled groups of electrodes through adjustable resistances to the main feeding conductor, so that the same quantity of current per unit length of a line electrode, or per unit surface of a surface electrode would be supplied to the soil. In general, however, such bothersome electrode arrangements are not practical. One obtains much simpler relations if one constructs the field electrodes as point electrodes with a greater number of individual groundings laid close to one another, which one arranges at such a distance from one another that the region to be measured does not cover more than the middle third between the field electrodes. Then the equipotential surfaces within this narrower region in the undisturbed subsoil are already almost smooth, and, further, the depth effect, which corresponds in the first place with the distance between field electrodes, and is noticeably greater.

An example of a somewhat complicated arrangement of the field electrodes is given by Ambronn (409), in order to screen the current line field from disturbing bodies already known, by spatially suitably distributed electrodes which have been supplied with correspondingly regulated currents. This method has special importance in the search for oozing alkaline places in

salt mines. The trickling alkalies separated from the ground water by the usually dry, and therefore insulated, covering formations in the extent of the works, form a good conducting path for the electric current between an electrode above and one below ground. The current lines concentrate again, after they have radiated in all directions from the electrodes, at the oozing places. Besides these oozing places, the shafts also form a good conducting connection between the ground water and the strike system. By using screen electrodes, properly distributed, and properly equalized as to their conducting resistance, the disturbing influence of the shafts can be entirely

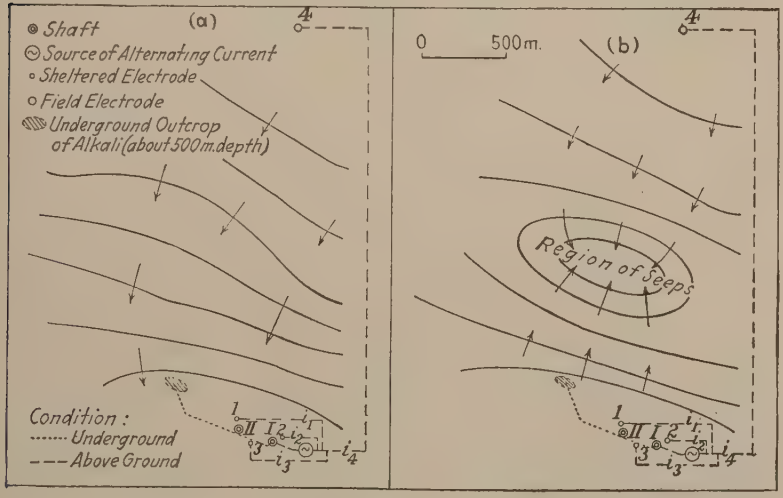

FIG. 53.

suppressed. Figure 53 shows an example of the application of such a screening electrode. In Picture *a*, the amplitude of the current i_1 and i_3 to the screening electrodes 1 and 3, respectively, has not been properly equalized with the current i_4 to the field electrode 4. In Picture *b*, the current, i_4, has been reduced, and the sinking of the current lines (which emanate partially from the field electrode 4, and partially from the screening electrodes 1 and 3) in the region of oozing is now shown by the measured lines of equipotential. Further examples of such applications of spatially distributed field-electrode systems, all carried out under the direction of Ambronn, are given by Brinckmeier (248) and Hülsenbeck (749*a*). The latter

investigation was carried out to establish from above ground, the origin of mine water in a coal mine.

In case there is no such special reason for using a complicated electrode arrangement, it appears more expedient to use point-formed electrodes in place of more complicated line- or surface-like electrode arrangements, and to place these at a correspondingly greater distance from one another. In the middle third of the field, then, the current lines are also fairly parallel, and one has, at the same time, the advantage of an essentially greater depth effect.

For controls and checks, one will generally use several set-ups with different field electrodes situated along lines which intersect,

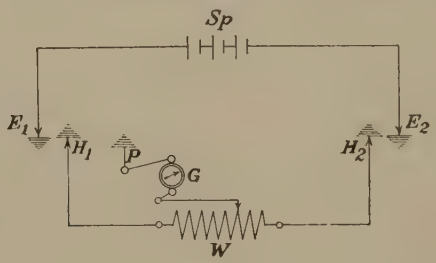

FIG. 54.

for instance, at 90° or at 60° and 120°. Gella (1238) proposed to erect simultaneously several systems of field electrodes with pivotal axes and to connect them by an automatic commutator periodically connecting the current source to the different systems. In this way indeed the numerous walks through the country are saved, but there is the disadvantage that the measurements themselves must be made at fixed times. Furthermore this is possible in practice only for very simple and rough measurements.

The measuring of the form of the equipotential lines in these artificially stimulated fields is done just as in the natural fields. The determination of the potentials of individual points P in the potential field can also be made here by comparison with the known potential distribution along a high resistance W whose ends are connected at the points H_1 and H_2 in the vicinity of the electrodes E_1 and E_2, so that the very high and easily variable potential fall in the immediate vicinity of the electrodes is eliminated, as can be seen from Fig. 54. Absence of current

in the galvanometer G shows that the potential at the point P is equal to the potential at the point of contact with the resistance R.

In order to be able to differentiate the artificial direct currents from natural earth currents perhaps flowing in the subsoil, Schlumberger (1369, p. 35) (see also Kelly (803)) proposed to reverse rapidly the field-exciting voltage Sp, so that the throw of the direct current galvanometer G, due to the artificial field current, periodically reverses, while the natural earth currents always cause deflection in the same direction.

It often seems expedient to survey first by steplike advances along the equipotential lines, and then to map them, in order to determine the distribution of the absolute value of the potential along the profile line crossing the system. At the place of crossing with the base line thus measured, one can read the potential corresponding to each curve.

Another method of approximate determination of the potential gradient is given by Ambronn (405) when, in an auxiliary current circuit perpendicular to the equipotential lines between two wells in which a variable resistance had been inserted, he measured pairs of values of resistance and current strengths and calculated from them the electromotive force by Ohm's law.

Wenner (1599) gives a method belonging here and derives the formula for a quantitative calculation. In an electrical region, to be regarded as homogeneous, there are placed four boreholes at the same distance a from one another and with the same depth b, in the bottom of each of which a non-polarizable electrode is placed. The two outer electrodes (Fig. 55) serve as conductors of the current J, and the potential e is measured between the two inner ones. Then $R = e/J$ is the magnitude of the resistance. Wenner shows then that with such an arrangement, the resistance ρ of a cubic centimeter of the ground (soil) material in question (the reciprocal conductivity) is

$$\rho = \frac{4\pi a R}{1 + \dfrac{2a}{\sqrt{a^2 + 4b^2}} - \dfrac{2a}{\sqrt{4a^2 + 4b^2}}} = \frac{4\pi a R}{n}$$

If the wells are all shallow in relation to their distance apart, *i.e.*, ρ is very much smaller than a, then $\rho = 2\pi \cdot a \cdot R$; on the other hand, if the wells are deep with respect to their distance apart, *i.e.*, small with respect to b, then $\rho = 4\pi \cdot a \cdot R$. Wenner

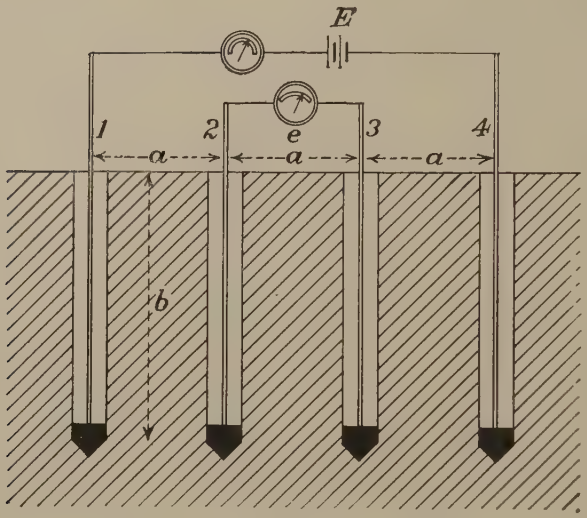

FIG. 55.

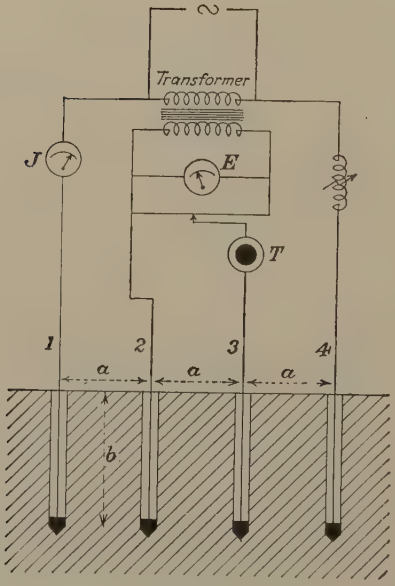

FIG. 56.

also discusses the cases in which the wells have different depths, at varying distances and no longer arranged in a straight line, and finally also gives means of carrying out the measurements with use of alternating currents (Fig. 56), in which case one can use a telephone T as indicating instrument. In order to avoid disturbing phase displacements, however, this must be done with very slow alternating current.

By means of a similar method, in larger regions, for example, one can determine the distribution of the salt content of the ground water, since its electrical conductivity is proportional to the salt content, and can thereby establish in suitable cases the position of salt domes on whose flanks perhaps it may be economical to drill for oil. Similarly, according to Gish (553, 553*b*) and Gish and Rooney (1298), this method can serve for the determination of the electrical conductivity of soil formations in the spatial entirety and in their natural deposition, which at times is of importance for scientific purposes. The other electrical methods are generally limited to the estimation of conductivity differences or quotients, which, in practical geophysics, are of economic importance.

Direct current appears to be used for earth investigations only by Schlumberger and his school. It has the advantage that no disturbances whatever can appear through induction or capacity phenomena. However, by means of vacuum tube amplifiers the disadvantages of alternating current in the investigation of large regions may be more than compensated by the much more convenient, lighter, and cheaper apparatus. Alternating current, with an appropriate method of measuring, also opens important and far-reaching possibilities of investigation, which are entirely inaccessible to the direct-current methods. Bartels (613*d*, p. 571 *et seq.*) unfortunately did not take these facts sufficiently into account, if he thought that the various electrical methods of prospecting differ from one another only in details.

The attempts of Daft and Williams (1525) (see also Petersson (1224)), at the beginning of the twentieth century, to supply alternating current to the soil by means of an extremely complicated apparatus, and to draw conclusions concerning the structure of the subsoil from the sound of a telephone inserted between two tuning forks, need only be mentioned here. The method has long been abandoned. A more recent attempt of Smalzi (see Fordham (469*a*)) in a similar direction seems entirely hopeless. From resistance determinations in the soil between wells by

means of the Wheatstone bridge arrangement, Brown (252) sought to find conducting ores which should decrease the resistance.

Simple resistance measurements, however, can attain practical importance only if it is a question of the investigation of the linear structure. An example of this is formed by the influx of alkalies in potash works, which are often separated from the ground water (meteoric water) in narrow tube- or fissure-like paths. Then if one immerses one electrode in ground water, and connects the other to the outcrop of the alkaline waters in the underground drift, the resistance between these two points will give a hint as to whether the emerging alkalies are connected with the ground water or whether they arise from solution of alkalies shut off in the salt formation (so-called original alkalies). Peust (1227) sought to pursue this idea practically; but without success, since the alkalies in the vicinity of the place of emergence have already been so soaked that along the drift a very good conducting connection also leads from the shaft to the ground water. A shunt to the alkali influx through the formation is thus formed. Through the systematic measurement of the resistances between a great number of points which are laid out in the vicinity between the outcrop of alkali and the shaft, one can derive with sufficient accuracy, according to Ambronn, differentially the contact resistances from the electrodes in the soaked formation and the resistance of the enclosing circuit through the formation alone. Koenigsberger (839*b*) would apply electrical-resistance measurements to the establishing of the approach of drifts to alkali-bearing disturbances in salt mining. In general, however, the measurement of equipotential lines (or surfaces underground) or the magnetic field of the soil current offers a more troublesome, but a safer, way of solving such problems (see also Hunkel (750*a*)).

Pure resistance measurements find a wider practical use in the investigation of the formations in devitrification works according to the cement method. The method was developed by Leimbach (417, 936) and also described by Ambronn (23). In sinking a shaft in a formation, if one arrives, for instance, at a point where the water penetration hinders the progress of the work, then the shaft is sealed from below with a cement plug. In order to close the fissures in the deeper water-bearing formations, one drills one or several rims around the bottom of the shaft obliquely outward from the hole, which has been closed above with a

stopcock, and through which later cement paste under high pressure will be pressed into the formation. In order to establish where the main clefts in the formation lie, one observes the quantity of water appearing in the drilling of this hole. In the tapping of fissures and the like, this water suddenly increases. In electrical testing a probe with insulated feeder is introduced by steps into the hole to be tested, and the electrical resistance between it and the shaft wall or an opposite electrode placed in another well, which can be advanced in a similar manner, is measured. The passing of water-bearing fissures or fissured soaked regions makes itself clearly and characteristically noticeable in the change of the resistance between the probes. By measuring the increase of resistance while cementing a formation, one can follow the progress of the work and determine how well the cement is setting.

The Investigation of the Subsoil by Means of Alternating-current Fields.—In using alternating currents for producing an electrical-current field in the subsoil, one must employ especial care in laying the conductors from the generator to the field electrodes, since induction and capacity effects may be caused by these conductors. Induction effects can be minimized when bifilar connections can be made. Further to decrease the effect, one can lay the conductors on the line joining the electrodes, so that their influence will be symmetrical with respect to the electrodes. One can also lead the current from the generator to the electrodes in a wide arc around and on both sides of the outer extensions of the electrode connections, so that the middle field between the two field electrodes may be only slightly influenced by induction effects. The capacity effects of loading on the inductive effects can usually be disregarded. One can also use branching electrodes. In alternating-current measurements, if one chooses a very small separation for the field electrodes, as did, for example, Gella (531) and Krahmann (867*a*), one obtains in the main part of the field, an essentially wide-open amplitude of ellipses of the tensional vectors in the soil, as well as the magnetic vectors in the air. The accuracy of measurement will then be exceptionally poor if one uses the older exploring-rod or exploring-coil methods in which one neglected this ellipticity. Upon this fact may depend the ideas of different authors (Gella (531), Krahmann (867*a*), Mueser (1140*c*)) that the exploring-rod measurements are less reliable than the exploring coil measure-

ments; for, when using the small separations of the field electrodes, such as were used in these measurements, one may find in the homogeneous subsoil itself in directions inclined about 45° to the electrode connecting lines, many positions at which the potential vector in the soil is completely circularly polarized, the current in the probe circumference thus being entirely independent of the azimuth of the probe conduction, so that the gaging of equipotential lines at this place is impossible. The magnetic vectors show smaller axial relations in their elliptical amplitudes (about one-third), since they, being integral effects of the current paths in the entire region of investigation, are less influenced by the local current distribution. In this fact, from the standpoint of practical soil investigation, lies its main disadvantage. First, if according to Ambronn, one measures the ellipses of the potential and the magnetic vectors completely, one can turn this great disadvantage of the narrow (inner) arrangement of the field electrodes occasionally into an advantage.

Alternating current can also be transferred inductively or capacitively into the subsoil without any metallic conducting connection of the generator to the soil. However, while the inductive transference possesses a very great practical importance, above all in desert regions, that of the capacitive transference may be very slight. The methods suggested by Riley (1295*a*) can scarcely be recommended. A closed circuit in which alternating current flows induces induction currents in the soil. Such circuits, closed in themselves, can be laid on the surface of the earth or in shafts, drifts, cross-cuts, or subterranean structures of mines. In conductive formations, then, eddy currents are produced by induction, and these cause a distortion of the normal field of the inducing circuit. Deposits of different conductivities distort the normal distribution of this current in a characteristic manner. Since in this way one avoids the usually high constant resistance of the field electrodes and can make the inducing circuit of heavy copper wire with very little resistance, one obtains by this method a very efficient utilization of the electric energy supplied. This method of inducing currents, together with a simple receiver, is useful when driving along a drift in a vein system with leaders of conducting ores or ore pockets above or below the level of the drift, and also to detect the proximity of an ore body when driving a drift.

The transference of electric alternating-current energy into the soil through capacity can assume large values only when high potentials are used, and then may serve occasionally to detect conducting deposits in the vicinity of high-tension conductors by vortical currents produced in these. The capacitative-influence phenomena become practically important only when high-frequency alternating currents are used.

The Detection of the Course of the Alternating Current in the Subsoil.—Measurement of the distribution of alternating current in the subsoil in order to locate disturbances which are caused by deposits of divergent conductivity are first carried out just as in direct-current fields. Telephonic receivers can now be used as the detecting instrument, while iron rods serve as the probe electrodes. Such measurements were first carried out and described by Bergström (170), who used a spark coil as an alternating-current source (see also Bergholm 169*b*).

If one produces an alternating current in the subsoil, however, the position and course of the current lines at every moment are dependent upon the phase of this alternating current. The direction of the current and equipotential lines rotate during each cycle of the alternating current in such a way that the current vector always describes a plane ellipse. In general, therefore, it is impossible to find positions for the points P and Q (Fig. 49) such that there will be no sound in the telephone receivers. Bartels (613*d*, p. 571 *et seq.*) has completely overlooked this basic difference between the direct- and the alternating-current methods of earth investigation. Müller (1148*a*) also draws few practical conclusions from his theoretical statements.

This basic difference between the two methods is clearly evident from an analysis of the process of the production of the alternating current in the soil. In the production of an alternating-current field in the soil, there arise different current systems which overlie one another. This has also been recognized by Heine (681*a*), but it has not been logically carried through. The following considerations show, first, how these different currents arise in the soil, and second, that in practice one can isolate analytically the various components of the observed current.

First a current field is formed by the alternating electromotive force between the field electrodes. This field is almost in phase with the alternating electromotive force, since the impedance of the alternating-current circuit above the soil between the field

electrodes is essentially resistive in nature. All current lines of this current system begin and end at the field electrodes, exactly as in the distribution shown for direct current in Figs. 51 and 52. The equipotential lines for this current surround the electrodes. A certain distortion of the current lines, as well as the equipotential lines of the alternating-current system as contrasted with the direct-current system, will be produced by the reaction of the current lines on one another, and perhaps also through electromagnetic reaction with magnetic or magnetizable materials in the earth. On the kind and magnitude of distortion brought about in such a manner, there have been no investigations up to the present. Still, reference should be made to related problems, and also to the investigations of Lamb (895), Zschaage (1669), Reich and Fischer (1290), Lühr (1000*b*), Rüdenberg (1315), Brauns (241), Mayr (1066), Pollaczek (1245*a*), Haberland (620*a*), Breisig (242*a*).

Further, displacements of the equipotential lines in the alternating-current field in contrast to the direct-current field between similar field electrodes are possible, if the electrical properties of parts of the soil are dependent upon the frequency of the alternating current. Capacity effects are important here if the galvanic conductivity of formations is so small that the displacement current in the dielectric attains the order of magnitude of the conductive current, and if the potential gradient is high because of the geologic condition of the subsoil in the region concerned. This holds, for instance, for a completely dry quartz vein within a conducting basal formation. The basal formation then represents the plates of a condenser whose dielectric is formed by the non-conducting quartz mass. The amplitude of the displacement current, and therefore of the conducting current corresponding to it in the connected conductive material, is therefore proportional to the frequency of the alternating current. The apparent resistance R_e which a nonconductor opposes to the soil currents is calculated according to Ambronn (33*e*) as

$$R_e = \frac{4\pi}{\omega\delta} \cdot 9 \cdot 10^{11} \text{ ohms (per cubic centimeter)},$$

where $\omega = 2\pi\nu$, ν = frequency of the current, and δ is the dielectric constant. This resistance is thus the highest resistance value which a ground element of zero conductivity can have.

A small table gives the limiting resistance values for current frequencies $\omega = 300$, 3,000, and 30,000 ($\nu = 50$, 500, 5,000 cycles per second) and for dielectric constants $\delta = 1$, 2, 5 and 10.

TABLE XV*a*

δ	$\omega = 300$	3,000	30,000
1	40.10^9	40.10^8	40.10^7
2	20.10^9	20.10^8	20.10^7
5	8.10^9	8.10^8	8.10^7
10	4.10^9	4.10^8	4.10^7

In practice there comes into consideration above all the circuit frequency $\omega = 3{,}000$ and the dielectric constant $\delta = 10$, under which conditions the specific resistance in the interior of the earth can never rise above

$$4 \times 10^8 \text{ ohms per cubic centimeter.}$$

According to this, the calculations of Ibach (762) are weak. The displacement-current component leads the conductive current by 90°. On account of the dependence of the displacement current upon the frequency, differences in the character of the tone in the telephone may appear as the movable probe is displaced in different directions from the average equipotential line, if there are harmonics present in the output of the generator feeding the field electrodes. In exact measurements, one must, therefore, minimize the effect of harmonics by tuning the receivers, or taking other suitable precautions.

Besides this current system, whose source lies in the field electrodes and the free charges possibly appearing in poorly conducting deposits, there exists a second system which is caused by the inductive effect of the conductor of the alternating current from the generator to the electrodes. Its exact form is determined by the position of these conductors. This current field, brought about by induction, is a vortical field. It possesses no potential, and all current lines are closed on themselves. The electromotive forces which it produces are spatially distributed. Indeed, one can also establish in it lines whose points, connected with one another, produce no current in the connecting conductor. Thus, in a sense, these can be designated as equipotential lines. These lines do not surround the electrodes, however, but form stars or vortical figures about centers whose form and position are largely dependent upon the spatial distribution of the electric conductivity in the subsoil.

If the source of the alternating current is in the line connecting the electrodes, and if the conductors go along this line of symmetry to both electrodes, then the lines of forces induced in an electrically homogeneous soil will form a vertical semicircle about the conductor connecting the electrodes as an axis. This semicircle ends at the surface of the earth at both sides of this line in a vortex flowing around in the opposite direction from the current. Figure 57 shows, in the half designated by I, the distribution of the alternating current emanating from the two electrodes E_1 and E_2, while in half II the distribution of the vortical-current field induced in the soil is sketched schematically.

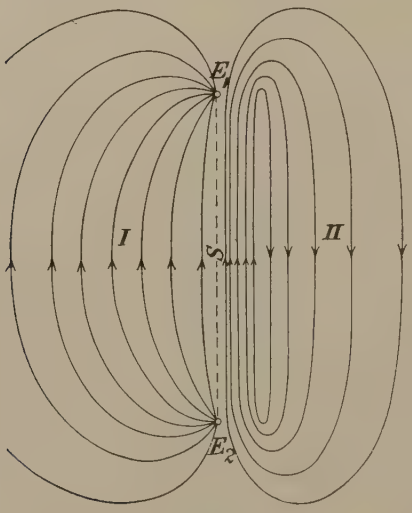

Fig. 57.

If deposits of different electrical conductivity are present in the subsoil, then currents are formed in their vicinity which overlie the main system.

The induced vortical-current system is displaced about 90° in phase with respect to the inducing current and thus also with respect to the generator electromotive force. While the potential field (I) carries predominantly working current, the vortical field (II) corresponds to eddy currents. The phase of (I) is not exactly zero because of the slight self-induction of the circuit, and the phase of (II) is not entirely 90° because of the ohmic resistance of the soil for (II).

The current excited through the capacity of the conductors to the field electrodes possesses, furthermore, a divergent field distribution with surface-like source regions and different phases. On the surface of the earth, in general, it is only very weak. Within regions of poor conductors which are bounded by good conductors, these components can even overbalance those above. In high-frequency fields they can first produce sufficient energy content to make themselves practically noticeable. Still frequencies above 2,000 per second in conducting subsoil

are unsuitable, since the entire current is concentrated in the immediate vicinity of the surface and the method has no depth effect.

If the soil currents are excited by a sinusoidal electromotive force, then all the current components individually characterized above are collected at each place in the field into a resulting current vector whose free end describes a plane ellipse. One can then consider this ellipse as composed of two linear vibrations of opposite phase displacement grouped in various positions along the two diameters of the ellipse. If one chooses the phase displacement of these two vibrations as 90°, then the diameter of the ellipse belonging thereto forms the conjugate diameter of the same. At each phase φ of the exciting electromotive force, there are, then, at each place in the current field, two linear vibrating components of the soil current, one of which is in phase with the exciting electromotive force, while the phase of the other is displaced about 90° with respect to the exciting electromotive force, and which together give the momentary field of the soil current, corresponding to this phase of the exciting tension. Each of these momentary fields is a function of the electrical structure of the subsoil. If one knows the form of the vibration ellipse and (splitting it into the two components displaced in phase 90° from one another) the phase displacement belonging to some one of its diameters, with reference to the exciting electromotive force, *i.e.*, a momentary field belonging to a phase φ, then all other momentary fields may be derived by construction or calculation. Likewise one can contrast the vibration ellipse from three linear vibrating vectors parallel to the axes of a right- or oblique-angled coordinate system, whose amplitude and phase displacement are determined with respect to the phase assumed as normal (for instance the phase of the exciting electromotive force).

The methods for measuring these current components in the soil displaced in phase with respect to one another, relative to the phase of the exciting tension, or with respect to the vibrations at an arbitrarily chosen place in the field, cannot be described here on account of patent rights; but it may be said that these methods may lead to entirely new and promising fields of electrical prospecting. Up to now this question has only been noted in general form by Ambronn (33, 33*i*, 33*k*, 33*l*). Later Zuschlag (1672) also refers to some related questions.

In soils with homogeneously distributed electrical conductivity, in the middle region of the current lines, the different components of the soil current, designated above, are parallel, or almost parallel, to one another; so that, in spite of the existing phase differences and independent of its intensity relations, the current vectoral ellipses and the magnetic-field vectoral ellipses become very flat. Naturally the immediate field of the conduction above ground, from the generator to the field electrodes, and the loop producing the soil current through induction, have a great influence on the form of the magnetic field, which also must be considered (see Sundberg (1500*c*), Meier (1067*a*), Friedl (486*a*)).

In larger deposits in the subsoil which are good conductors, induced vortical-current systems are formed, which overlie the normal field. Since the two current systems (I and II) no longer lie parallel to one another in the middle region between the electrodes, one obtains wide-open current vectoral ellipses there, making the measurement of the equipotential lines according to the old probe methods difficult if not entirely impossible. On swinging the movable probe at various angles about the rigid probe, the current strength in the probe circuit may change only very slightly. In this case one must then measure quantitatively the relative axial relations of these current vectoral ellipses, the azimuth of the great axis and phase distribution, perhaps the components vibrating in the direction of the great axis, with respect to the exciting current; or one must determine, as to amplitude and phase, the two linear vectors obtained by projection of the ellipse on the two axes of a right- or oblique-angled coordinate system.

Disturbances are produced also by currents in the probe loop, which are induced by the lines of force of the magnetic field of the soil current entering through the probe loop. In order to remove this, one can, besides the amplifier and rectifier V (Fig. 58), to which the galvanometer G is attached, according to Ambronn, insert a coil R in the conductor connecting the probes S_1 and S_2, whose winding is directed opposite to that of the probe loop. Since the probe loop is constructed downward from the spatial conductor of the subsoil, the area of the coil requisite for the compensation is to be determined for each specific case.

So long as it is a question of the general survey of a great region, one must often be content, on economic grounds, with

surveying and mapping only the average direction of the equipotential lines. If one works with a fixed distance of the searching probes (for instance 10 m.), then one can establish for each

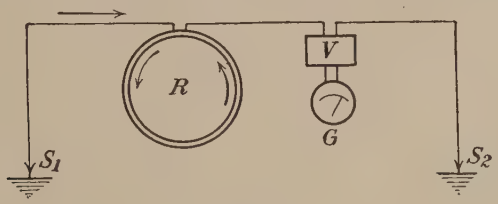

Fig. 58.

Fig. 58A.

location the signal strength in the telephone (for instance, measured by means of the shunted telephone method at the minimum position) and, by swinging the probe direction about

90°, the signal strength at maximum position perpendicular to the equipotential lines. It is, further, often expedient then to ascertain the "minimum breadth," that is, the breadth of the bands along the equipotential lines within which one is able to notice no great variation in the telephone of the probe circuit, with displacement of the movable probe. In this way one obtains at least an approximate survey of the structure of the vibration ellipses of the current vectors in the region under investigation. In disturbed regions, one must, however, measure accurately the current vectoral ellipses themselves. However, after one has constructed apparatus which is capable of making

Fig. 58B.

the quantitative measurement of the complete vibration ellipse at the same time (which one has also needed in the use of the usual equipotential-line methods with alternating current), one may, according to Ambronn (33*k*, *l*), carry out the electrical soil investigation by means of alternating current but still according to the complete ellipse method.

In support of the method of earth-current measurement with fixed electrodes and audibility method of wireless telegraphy, it has been proposed (320*b*, 540) to take the potential at three or four points arranged in triangles or quadrangles, and, with the help of coils, to produce a magnetic field corresponding to the earth field, whose properties could be measured by means of induction coils or magnets. These methods, however, may generally be much too clumsy in practice for field measurements.

The Measurement of the Magnetic Alternating Field of the Ground Current.—Through the measurement of the potential distribution there is determined only the current distribution in the uppermost film of the soil. Deposits of different conductivity in the ground can make themselves noticeable only in the potential distribution at the surface of the earth in so far as they indirectly influence the current distribution at places in the uppermost film which are accessible for measurement. The magnetic field at the surface of the earth, on the contrary, is composed of the individual effects of all the current elements in the entire space through which the current flows in proportion to their distance and direction, as well as the momentary current strength and current direction in them, according to the rule of vectoral addition.

This entirely basic difference between the measurement of the potential distribution and that of the magnetic field of the ground current is to be considered continually with the greatest care. The proposal of Rawen (1273) and Gella (529, 530) misses a consideration of this difference which is most important for the comprehension and the criticism of the electrical methods. The careful critique of Wilser (1631), as well as the considerations of Reich (1289, p. 265) on investigations carried out according to Gella's method on lignite and coal deposits, unfortunately do not go closely into the physical questions.[1]

[1] Krahmann, a collaborator of Gella's, gives (867*a*, p. 6; Pl. 2, 867*b*), as a basis for all his further explanations, a picture "electromagnetic lines of force" of the current flowing between two field electrodes in homogeneous ground; this illustration, however, shows in reality approximately the current lines of the component of the ground current which vibrates in phase with the exciting voltage. The magnetic lines of force stand in the middle of the field exactly perpendicular to the given curve. Plate 3, at the same place, is entirely unintelligible, where the "electromagnetic equipotential lines" there displayed possess no physical reality whatever. Compared with Gella's method of investigation, Sundberg (1500*a*) also raises authoritative considerations. Likewise a most recent, but very one-sided, report of Gella's (531) in misunderstanding of the actual processes, further asserts that current lines with exploring coils are surveyed on the surface of the earth. Besides, the data on the electrical conductivity of the ground formations in this treatise are given very misleadingly; thus, for instance, salt water is one of the best conductors in the subsoil that one knows, while the differences in the conductivity between oil and dry formations, on the contrary, in reality are practically vanishingly slight (see Table XV). Since a conductivity relation of at least 1,000 between the desired deposit and its surroundings is requisite for the possibility of a distinction of different

For the measurement of the electromagnetic alternating field produced by the earth current, one uses, according to Ambronn (28, 33, 33*k*, *l*), Sundberg (1499, 1500), Meier (1067*a*), Gella (531), Krahmann (867*a*), a free exploring coil or frame torsionally moving in space, of many turns of wire which is not too thin. The number of turns is proportional to the frequency of the soil current. Large pick-up of the ground current with small self-induction are to be striven for. Loose winding is therefore expedient. Attention must be paid to the fact that there are no large metallic masses in the region of the coil, since vortical currents will be excited which will falsify the observations. This precaution is to be observed more rigidly, the higher the frequency of the alternating current used. The impedance increase, through self-induction, can be compensated through tuning of the exploring coil to the frequency of the soil current in some manner. To the end of the exploring coil a telephone is attached, either immediately or after a vacuum-tube amplifier with two to four tubes. If one uses for the last tube of the amplifier a rectifier tube, then one can also determine quantitatively the magnitude of the induction in each position, in order to be able to measure the spatial curve which runs through the magnetic vector. On account of the difficulty of keeping the ground current itself and the amplification factor of the tube voltmeter temporally constant, the vibration ellipse is practically measured only by means of compensation apparatus as shown in Fig. 58A (Ambronn (33*k*, *l*) in which strength and phase of the tension induced in the exploring coil are quantitatively compared, directly or indirectly, with the strength and phase of the current supplied to the soil. The position of the exploring-coil plane in space is determined by compass and plumb line. A rotation of the exploring coil in its own plane is without influence on the induction in it.

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masses in the deeper subsoil, which alone comes into practical consideration, then, as Ambronn (33*c*) fully proves, if one inserts as possible highest value of the (capacitative) resistance of the soil material, according to page 173, the value

$$4 \times 10^8 \text{ ohm} \quad \text{cm.}^{-1},$$

soil materials with resistances of more than

$$4 \times 10^5 \text{ ohm} \quad \text{cm.}^{-1}$$

may no longer be differentiated from one another by means of electrical methods from the surface of the earth. Dry formations, oil-soaked sands, and the like, rock salt, etc., all fall in this group whose members are not further distinguishable among one another; so that already from this theoretical consideration the immediate search for oil as an insulator in the soil is completely impossible.

In order to determine the direction of the magnetic lines of force at a given point in a linear magnetic alternating field, such as the magnetic field of soil currents which has been considered up to the present, one seeks first a position of the exploring coil (frame) Fig. 58B in which the induction effect in it vanishes entirely or as completely as possible. In such case the magnetic lines of force and the major axis of its vibration ellipse lie in its winding plane. Since a rotation of the exploring coil in its plane can bring about no change in the induction, one characterizes the position of the exploring coil in space most simply by the direction of its axis which is perpendicular to its winding plane. If one determines yet a second position of the exploring coil in which the induction effect vanishes, then one obtains the direction of the magnetic lines of force at the measuring point as perpendicular to the plane laid through the two measured axial directions. This method is only applicable, however, if the vibration ellipse of the magnetic vector is very small.

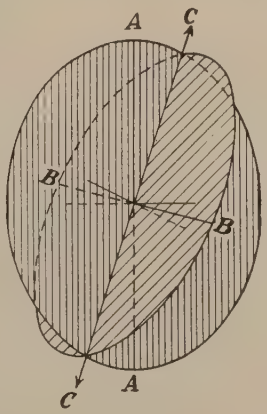


Fig. 59.

In practice, one usually proceeds so that one turns the exploring coil first about a vertical axis *A-A* (Fig. 59) lying in its winding plane. Then one swings the exploring coil around vertically 90°, and inclines it toward a horizontal axis *B-B* until the tone again vanishes. The intersecting line *C-C* of the two coil planes for which the tone (the induction) vanishes, is then the direction of the magnetic lines of force.

Another method for determining the direction of the magnetic lines of force of the electrical-current field in the subsoil depends upon the same principle as the induction inclinatorium treated on pp. 83 *et seq.* If one allows a coil to rotate in the field slowly about a chosen diameter laid in space, then the intensity of the current induced in it fluctuates with the frequency of its rotation. If the torsional axis coincides with the direction of the lines of force, then in a linear magnetic field the induction vanishes completely. In an elliptical field of force, however, the pulsations of the induced current and the tone in the telephone reach a minimum value only if the torsional axis of the frame coincides with the direction of the major axis of the vibration ellipse. In linear fields, the azimuth and incidence of the rotation axis in this position indicate forthwith the position of

the lines of force at the place of erection of the apparatus. The induced currents, according to Gella (1238), can either be directed over loops on the amplifying and measuring apparatus, or, according to Ambronn (411), be transferred inductively from the coils closed in themselves to the measuring contrivance (telephone or rectifier with galvanometer). For more exact investigations, this method is unserviceable for reasons given above.

The intensity of the magnetic field is determined by adjusting the plane of the exploring coil perpendicular to the direction of the magnetic lines of force thus established, whereby the maximum induction in the exploring coil is obtained. In general, one is content practically with a relative comparison of the intensities of the induced electromotive forces within an investigated region.

If, as was fully set forth in the treatment of equipotential line methods, and as is continually the case in practice, current systems with phases displaced with respect to one another, of a similar order of magnitude, overlie one another in the subsoil, the magnetic vector vibrates no longer linearly, but is free and moves with the sinusoidal exciting electromotive force in a plane ellipse. In this case one must determine the position of the elliptical plane in space, the axial relations, the direction of the main axis, and the phase distribution in its circumference relative to the phase of the exciting tension or to a zero point chosen but similar for all points in the region of investigation.

The search for the elliptical plane is very simply carried out, since only when the plane of the frame falls exactly in this elliptical plane does the induction in the frame completely vanish, as then also the magnetic vector always remains exactly within the plane of the frame. This position is always very easily established empirically with great accuracy by the complete disappearance of tone in the attached telephone, if one only suppresses the harmonics sufficiently, for which the vibration ellipse in general possesses another position than that of the basal vibration (usually 500 cycles per second). Zuschlag (1672) is in error when he remarks that, on account of the complementary effect of different current components in the soil with phase displaced with respect to one another, an exploring coil can remain induction-free in no position.

If one has so established the position of the elliptical plane in space (for instance through the azimuth λ of its long direction

and through its angle of incidence μ), then one obtains further the directions, length, and phase angle of its two axes, when the frame plane has been turned about 90°, so that it stands perpendicular to the plane of the ellipse and turns the frame now about an axis lying in its plane but standing perpendicular to the ellipse. The induction in the frame is then always proportional to the subtangent to the ellipse on the plane of the frame, so that the induction in the frame corresponds to the magnitude and phase of the great (small) axis of the ellipse if the plane of the frame falls in the small (great) axis of the vibration ellipse of the magnetic-field vector.

In this way one ascertains the angle σ, which is included by the great axis of the vibration ellipse with the direction of incidence of the elliptical plane, and then determines the amplitudes a and b, as well as the phase angles φ_a and φ_b of the great and small elliptical axes, where on general grounds φ_b must constantly equal $\varphi_a + 90°$. Six determinations independent of one another completely define such a plane vibration ellipse in space.

One can now take the distribution of these immediately measured determinations over the investigated region, perhaps also represented in form of a space model, as a basis for the geological explanation of the electrical measurements.

However, from these six determinations one can also derive the three linear components parallel to the axes of a coordinate system of vibrating vectors which together yield the above vibration ellipse. If, as usually happens in practice, one takes a rectangular coordinate system x, y, z as a basis, whose x-axis points to the north, y-axis to the east and z-axis perpendicularly upward, then the vibration ellipse defined above by the values of λ, μ, σ, a, b, and φ_a, may also be described by the amplitudes A_x, A_y, A_z, and the phase angles φ_x, φ_y, φ_z of these three linear vibrations parallel to the axes. A_x, A_y, A_z, φ_x, φ_y, φ_z are then obtained from the measured λ, μ, σ, a, b, and φ_a according to the following relations, if one inserts the abbreviations:

$$\sin\lambda \sin\mu = k,\ \sin\lambda\cos\mu = l,\ \cos\lambda\sin\mu = m,\ \cos\lambda\cos\mu = n,$$
$$\sin\lambda\sin\sigma = p,\ \sin\lambda\cos\sigma = q,\ \cos\lambda\sin\sigma = r,\ \cos\lambda\cos\sigma = s;$$

$$\left.\begin{aligned} A_x^2 &= a^2(l\cos\sigma - r)^2 + b^2(n\cdot\cos\sigma + p)^2 \\ A_y^2 &= a^2(l\sin\sigma - s)^2 + b^2(q - n\sin\sigma)^2 \\ A_z^2 &= a^2k^2 + b^2m^2 \end{aligned}\right\}$$

$$\left.\begin{aligned}
\tan \varphi_x &= \frac{a(q \cos \mu - r) \cos \varphi_a - b(s \cdot \cos \mu + p) \sin \varphi_a}{a(r - q \cos \mu) \sin \varphi_a + b(s \cdot \cos \mu + p) \cos \varphi_a} \\
\tan \varphi_b &= \frac{a(s - p \cos \mu) \cos \varphi_a + b(r \cos \mu + q) \sin \varphi_a}{a(p \cos \mu - s) \sin \varphi_a - b(r \cos \mu + q) \cos \varphi_a} \\
\tan \varphi_z &= \frac{a \sin \lambda \cos \varphi_a + b \cos \lambda \sin \varphi_a}{a \sin \lambda \sin \varphi_a + b \cos \lambda \cos \varphi_a}
\end{aligned}\right\}$$

Conversely, naturally one can also determine immediately by measurement in the field the three rectangular components A_x, A_y, A_z, besides the phase displacement belonging to them, when one adjusts the exploring-coil plane first vertically in the east-west or the north-south direction, and finally horizontally, and each time measures the induction in the exploring coil vectorally according to strength and phase by compensation against a normal voltage. This method is indeed simpler in measurement than the determination of the vibration ellipse itself, one can calculate from the six measured magnitudes also the determinations according to the following formulae. If, however, the vibration ellipses, as usual, are apparently flat and perhaps even unfortunately oriented towards the coordinate axes, then the calculated determinations become somewhat inaccurate, since small errors in the strengths and phases of the vectoral components can then attain very great influence in the determinations of the vibration ellipses.

The measured vectoral components may be determined in their temporal course by the equations

$$\begin{aligned}
X &= A_x \sin (\omega t + \varphi_x) \\
Y &= A_y \sin (\omega t + \varphi_y) \\
Z &= A_z \sin (\omega t + \varphi_z),
\end{aligned}$$

where ω indicates the circuit frequency, A_x, A_y, A_z further the amplitudes and φ_x, φ_y, φ_z the phase displacements of the components against the normal phase taken as a basis.

The phase angles φ_a and $\varphi_b = \varphi_a + 90°$ are found as solutions of the equation

$$\tan 2\varphi = \frac{A_x^2 \sin 2\varphi_x + A_y^2 \sin 2\varphi_y + A_z^2 \sin 2\varphi_z}{A_x^2 \cos 2\varphi_x + A_y^2 \cos 2\varphi_y + A_z^2 \cos 2\varphi_z}.$$

From this equation there result two values for 2φ, differing 180°; thus two values of φ, differing 90°, of which the one corresponds to the phase of the large, the other to the phase of the small, elliptical axis.

The lengths of the elliptical axes a and b are obtained, then, from the expressions:

$$a^2 = A_x^2 \sin^2 (\varphi_a + \varphi_x) + A_y^2 \sin^2 (\varphi_a + \varphi_y) + A_z^2 \sin^2 (\varphi_a + \varphi_z)$$
$$b^2 = A_x^2 \sin^2 (\varphi_b + \varphi_x) + A_y^2 \sin^2 (\varphi_b + \varphi_y) + A_z^2 \sin^2 (\varphi_b + \varphi_z).$$

Finally, the directions of the axes a and b in space are determined through their direction cosines against the three coordinate axes:

a includes the angles α_a, β_a, γ_a with the positive x, y, z axes;
b includes the angles α_b, β_b, γ_b with the positive x, y, z axes.

Then the directional cosines become

$$\cos \alpha_a = A_x \sin \frac{(\varphi_a + \varphi_x)}{a}, \quad \cos \beta_a = A_y \sin \frac{(\varphi_a + \varphi_y)}{a},$$
$$\cos \gamma_a = A_z \sin \frac{(\varphi_a + \varphi_z)}{a},$$
$$\cos \alpha_b = A_x \cos \frac{(\varphi_a + \varphi_x)}{b}, \quad \cos \beta_b = A_y \cos \frac{(\varphi_a + \varphi_y)}{b},$$
$$\cos \gamma_b = A_z \cos \frac{(\varphi_a + \varphi_z)}{b}$$

With this the vibration ellipse is determined completely according to position, form, and phase distribution. Complete calculations are given in (33*i*).

In practice, one naturally often allows many facilities in the measurement and calculations according to the problem to be solved, in order to lessen the expenditure of time; the representation of these special methods would lead us too far afield here.

Whether measurements of difference of direction and strength of the magnetic field of the ground currents at closely adjacent places, according to the methods of the Gesellschaft für praktische Geophysik (539), or according to Haalck (615), can be carried out practically with sufficient accuracy, in order to derive immediately the gradients of the field and to draw therefrom conclusions on the conductivity distribution in the subsoil for the purposes of geophysical prospecting, appears doubtful, since exactly this magnitude is disturbed in especially high degree by inhomogeneity in the immediate vicinity of the measuring point. As soon as the magnetic field is appreciably elliptically polarized—and over electrically inhomogeneous subsoil (which alone is of practical interest) this is always the case—these differential methods lose any meaning at all.

Since the methods of measuring the equipotential lines and gauning the magnetic field of the ground current thus use different effects of the current flowing in the ground, they not only mutually control themselves but also often complement each other at essential points. Especially with relation to depth effects do both methods keep strongly divergent from each other, so that just in this important direction the application of both methods together is of very great practical importance. The depth effects of a method naturally indicate this problem: up to what depth one can detect by measurement at the surface of the earth, a deposit with conductivity relations (conductivity relations 1,000) sufficiently different from its surroundings and of size sufficient for mining. If Krahmann (867*a*) assumes as depth effects that depth at which one can still detect the sending current, with erection of the receiving apparatus exactly at that depth, then such a definition of the "depth effects" possesses not the slightest significance for the practical application of electrical methods; it is much more apt to rouse completely misplaced and exaggerated conceptions of the range of methods in question, from which the severest disappointments must inevitably follow. In a suitable consideration of the depth effects of two methods, the controversy between Nathorst (1152) and Sundberg (1499) may also be settled. In general, the measurements of the potential field at the surface of the earth may yield results more comprehensive and richer than will measurements of the magnetic field, since the latter, because of its character as integral field, is less affected by local disturbances. These local disturbances, by their effect on the electric vector through overlapping, can be strongly depressed by the field components arising from the remaining current field. The preference which Gella (531), Krahmann (867*a*), and Mueser (1140*c*) show for magnetic-induction measurements may touch above all on the fact that, according to Ambronn (33*m*), the ellipses of the current or potential vectors in homogeneous subsoil become much broader as the distance of the electrodes from each other becomes smaller; so that with the very small distances between electrodes in the Elbof method, the vibration ellipses of the soil current are so wide open that one cannot accurately determine the direction of equipotential lines according to old methods of probing, since the minimum is too flat and deformed. There are, then, problems for whose solution the equipotential-line method is unsuitable or

inapplicable where the induction method may yield good results. An example carried out by Ambronn early in 1924, therefore, will be indicated in a few lines.

Under a poorly conducting covering formation there lies an almost horizontal formation which conducts well (for instance, a salt water formation in an oil region), whose depth is sought. At the surface of the earth over the conducting formation, then, two electrodes are placed at a sufficient distance from one another. The alternating-current generator or the branching point of the feeding conductor is placed in the middle between the electrodes. The return current in the subsoil between the electrodes will then seek to concentrate itself in the conducting formation, as long as the distance of the electrodes from one another is not too small. Also, if the conductivity in the covering formation is small, vortical currents can be produced in the deep formation through induction (for instance, by means of a closed loop), which possesses practical importance in investigations on water occurrences in the subsoil of desert regions. The strength of the vortical current depends also on the conductivity of the deep water, which is proportional to its salt content, so that in this way a solution may be obtained to an extremely important economic question (see also Friede (486*a*)).

The magnetic field of the soil current overlies that which is produced by the current flowing in the conductor connecting the electrodes. The field produced by these latter currents surrounds the conductor in circles whose field strength decreases with the distance (see Betz (181*a*)). If one thus measures the entire field in the above-described manner by means of exploring coils, one can derive the field of the ground current alone, approximately, through vectoral subtraction. Here also attention must be paid to the collection of field components displaced in phase with respect to one another. In general, one measures the field distribution along a base cutting the line connecting the electrodes perpendicularly at its center. Consequently, if one has established a normal value for the electrode distance for all time, one can obtain investigation results immediately comparable with one another. In more recent times Sundberg (1500*c*) has made note of this method, without, however, considering the ellipticity of the magnetic vectors. Friedl (486*a*) has published a beautiful example of such a measurement in the Austrian oil fields for the purpose of finding and mapping the salt water horizon. This measurement method thus uses phenomena similar to the use of

ocean cables, through which alternating current flows, as pilot cables, relative to which reference may be made to the expositions of Lichte (954), Butterworth (281), Drysdale (361), and others. Loth (980) also has concerned himself with like problems but in a way too simple for success.

Some mention may still be added relative to a suitable exposition of the simple potential and induction measurements obtained in the field, on which Ambronn (33, p. 99) has already extensively reported. The measurements themselves are carried out by the shunted-telephone method to determine approximately the signal strength, and consider the ellipticity only qualitatively.

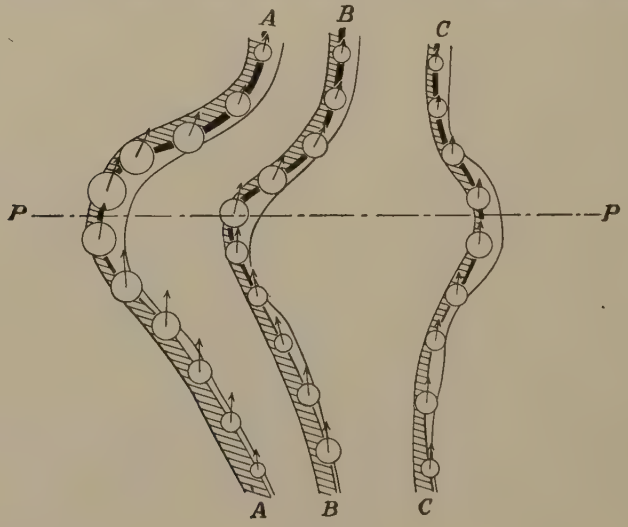


Fig. 60.

An ellipticity of the magnetic vectors is entirely disregarded. Figure 60 shows this exposition in a schematic example, for a region disturbed by a better-conducting deposit *P-P*. *AA*, *BB*, *CC* are three equipotential lines. The breadth of the equipotential lines themselves indicates the signal strength in the telephone (current strength) with adjustment of the two exploratory probes in the "minimum direction." The breadth of the shaded areas on the left side of the equipotential lines gives the signal strength (current strength) with the position of the exploratory probes perpendicular to the direction of the equipotential lines. The test probes are arranged always at a normal distance from one another (for instance 10 m.). The

distance between the thin lines which are always at the right of the equipotential lines gives a measure of the "minimum breadth" (see p. 178). This distance becomes smaller as the minimum formed over the equipotential lines becomes sharper, and the vibration ellipse of the ground current becomes narrower. The measurements with the exploring coil allow the measured magnetic force to be split up into two components, of which the one is directed perpendicularly downward, the other horizontally. The latter is designated according to size and direction by the arrows, the former by the areas of the circles drawn around the measuring point. The diagram would be especially instructive if one drew in the equipotential lines with their complementary signatures in a relief picture of the measured region, and indicated the magnetic forces deviating from the above diagram in direction and strength by pieces of wire of corresponding length. The model thus obtained is, however, only stereoscoptically reproducable and therefore not suited for printing. This diagram is to be considered as already obsolete, since today one must prefer the quantitative exposition of the determined parts of the vibration ellipses, etc., either the ellipse itself or the system of equipotential lines, current lines, or lines of magnetic force in an instantaneous field belonging to a characteristic phase φ, or else a graphical representation of the magnitude and phase displacement of the rectangular vectoral components representing the vibration ellipses.

According to the different methods of earth investigation by means of electrical measurements, practical investigations have already been carried out in great number; the development of geophysical methods in general by preeminently commercial organizations, and the utilization of the investigations carried out for industrial purposes has, however, the disadvantage that in the working out of the problem itself, the scientific importance unfortunately must often give way to economic considerations on financial grounds. The regrettable consequence of this is that there have been published scarcely any complete measurements of larger regions, which are suitable as examples of an assistance of practical geology by electrical methods. A great number of researches are known by Swedish investigators, for instance, Lundberg (1001, 1002, 1002*a*), Sundberg (1500, 1500*a*, 1500*b*, 1500*c*), Sundberg, Lundberg and Ecklund (1500*d*), Mortensen (1137). Special reference is made to the detailed discussion

and example in (1500*d*). Unfortunately these very comprehensive measurements were carried out in great part by means of Nathorst's linear electrodes, which are usable (p. 162) only under such abnormally favorable geologic relations as we find in the Swedish ore occurrences, where seams of the best conducting ore, over 50 m. thick lie under a few dozen meters of young morainic rubble. Figure 61 gives a small section of such a measurement. However, Swedish geophysicists have also employed the inductive production of soil currents and the measurement of the magnetic field of the soil current by means of the exploring coil, of which numerous very instructive examples are given in the literature cited above.

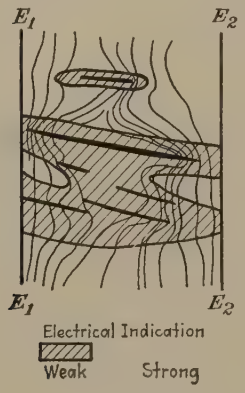


Fig. 61.

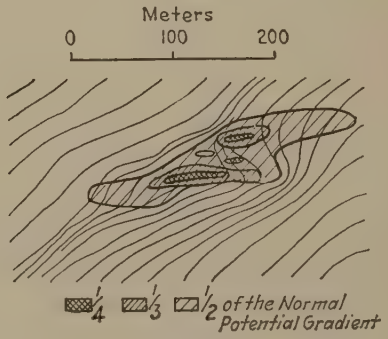


Fig. 62.

A sector of another equipotential line survey carried out by Lundberg in the Bjurfors ore field in Sweden is shown in Fig. 62. In this the disturbed region is still further analyzed in that the potential gradient perpendicular to the equipotential lines is derived and recorded. Since the ores which conduct well effect potential compensation, the potential gradient diminishes over the ore, and the region of potential gradient is lessened to $\frac{1}{4}$, $\frac{1}{3}$, and $\frac{1}{2}$. This therefore indicates the position of the ore deposits in very clear manner.

The reports of Koch (825) and Runge (1331, 1332) on measurements in Germany, carried out under the direction of Ambronn, give only a portion of the measurements actually carried out (the magnetic field was also measured) and scarcely consider the physical questions. Moore and Ebbutt (1136*a*) report on

electrical investigations on the Brittania copper mine; Fritsche (489*a*) gives measurements from northern Quebec; Möller (1132*b*) describes some measurements from Cornwall, which propose to show the electrical discovery of galena and sphalerite. Meanwhile, it must be noted that sphalerite, as a complete non-conductor, is not discoverable by electrical measurements. Krahmann (867*b*) also gives some examples of electrical investigations in ore regions and graphite-mine fields, but because of entirely erroneous conceptions and data on the peculiarity of the method of measurement used, these are scarcely valid. Finally, one may mention the most recent communication of Mortensen (1137). Great attention is given at present to the question as to whether oil deposits, as non-conductors, can be found directly by means of electrical methods. Gella (530, 531), Krahmann (867*a*, *b*), Ibach (762), Reich (1289*d*), Koenigsberger (839*d*), believe that the electrical conductivity of oil deposits is so much less than the soil formations usually occurring in oil regions that one can discover and delineate the oil-bearing formations by measurement of the distribution of alternating current introduced at the surface of the earth. On the contrary, it is emphasized by Ambronn (27*a*, 33*a*, *b*, *c*, *e*), Meyer (1067*a*), Ostermeyer (1206*a*), Sundberg (1500*c*), Friedl (486*a*), that such a direct distinction of the oil deposits from their surroundings is unfortunately impossible by electrical methods. First, one cannot compare the electrical properties of oil as found in nature with those of pure refined oils. The salt water impurities always present, for instance, raise the conductivity very considerably. Besides, in oil regions there are present other materials which are just as poor or worse conductors, such as dry rock and rock salt. Such substances may even occupy more space than the associated oil deposits. The electrical methods can thus give no unequivocal results. Ambronn (33*e*) also refers to the fact that poor conductors in the ground are penetrated by alternating currents as displacement currents, so that there is a natural upper limit of resistance beyond which different poor conductors in the subsoil can no longer be separated from one another, a consideration whose correctness Sundberg (1500*c*) has impressively demonstrated by experiment. Finally, there are the salt-water horizons constantly present in oil regions, which, being excellent conductors, concentrate the ground current, and completely mask slight differences in conductivity between poorly conducting deposits. The possibility of finding oil as a

non-conductor directly by means of electrical measurements must therefore be ruled out.[1]

On the other hand, electrical measurements can be employed for the geophysical mapping of the salt-water horizons, as has been described on p. 187. While such measurements as those made by Ambronn in 1924 on the Wietze-Steinförde salt dome with good results unfortunately could not be published, Friedl (486*a*), has now published some very beautiful examples of this method in Austrian oil fields, which prove the great practical importance of this method. The complete measurement of the vibration ellipses of the magnetic-field vectors, as suggested by Ambronn, will increase the accuracy still more.

High-frequency Fields.—The electrical methods of earth exploration mentioned thus far use either direct current or low- to medium-frequency alternating current, mainly about 500 cycles. For these frequencies the electrical field in the entire region of investigation is considered as a pure current field. When investigating regions some kilometers in greatest extent, one can use frequencies up to 5,000 to 10,000 cycles per second. In some cases, raising the frequency may be advantageous. The inductive effect of the soil current on the exploring coil used for measuring the magnetic field then increases, and one reaches regions of frequency within which the probe spool can be used more conveniently. Also, from the changes of the form, position, and phase distribution of the vibration ellipses of the current vectors and of the magnetic vectors as the frequency of the field current is varied, one can often derive important conclusions concerning the condition of the subsoil. It must be observed, however, that the depth effect decreases rapidly with rising frequency.

If one goes over into the still higher frequencies used in wireless telegraphy, however, then one arrives in another region of investigation, in which zealous work has been done for many years. With a suitable form of transmitting apparatus, these high frequencies give rise to an electrical radiation, which, besides being useful for wireless telegraphy and telephony, can

[1] The examples given by Krahmann (867*a*) for electrical measurements in oil regions are not usable, since the physical significance of the so-called "current lines" or "electromagnetic force lines" is not clear. Also, the geologic structure of the subsoil, in which, besides oil-impregnated formations, surely there are present also non-conducting dry masses, as well as excellently conducting salt-water horizons (possibly also non-conducting salt masses), is entirely unknown.

be used to broaden the realm of applied electrical methods of investigation notably and basically. This radiation, in contrast with the electric currents which are confined to conducting material, extends unhindered into nonconductors.

To go into the complete theory of these electromagnetic methods of investigation would overstep the bounds of the space

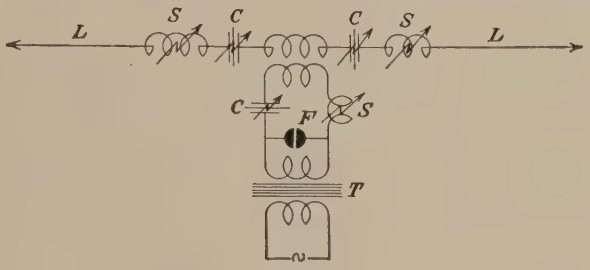


FIG. 63.

at disposal here. Only the general bases may be briefly explained. Exhaustive expositions on the production, the transmission, and the reception of high-frequency electric vibrations and waves are given by Zenneck and Rukop (1663), Geitler (528), Jäger (757), Nesper (1159), Ollendorff (1196*c*), Lertes (943).

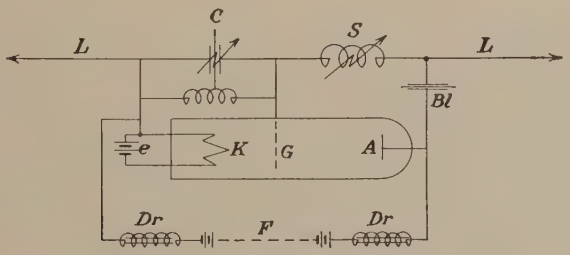


FIG. 64.

Relative to the production of electric vibrations in the sending apparatus for electric waves by means of spark and tube transmitters, let reference be made to the literature cited above. For the purpose of earth investigation by means of these electromagnetic waves, linear antennae have been almost entirely employed up to the present time. These antennae consist of straight wire, in which alternating currents of the desired frequency are produced. Figures 63 and 64 show schematically the

arrangement of a discharge spark or tube transmitter, both attached to a linear symmetrical antenna. In the figures, S indicates inductance, C capacity, T a t ansformer, F the spark plug, A the anode, C the grid, K the filament of the transmitting tube, Dr the choke coils, Bl a blocking condenser, E and e batteries, L the antenna wires. In a linear antenna, then, the electric charge swings periodically back and forth, and it is found in each cycle once in each half of the antenna as a static charge, while in the intermediate time there flows through the mid-portion of the antenna an electrical current, which produces a field of magnetic force about the antenna. Instead of building the antennae of two linear wires, one can, as is usual in wireless telegraphy, use an antenna and a ground. For the purposes of earth investigation, however, we are generally interested only in the ungrounded symmetrical antennae, since a satisfactory ground can seldom be found. A grounding underground on the bars of the "earth conductors" of the transformers is impossible, since these are not grounds in the sense of wireless telegraphy. The waves run in this case much more along the conductors thus used, extend themselves in more entirely uncontrollable manner in mines, and may badly distort the observations.

Radiating electromagnetic waves by large loops carrying alternating currents of the desired frequency, while less efficient, often have essential advantages. On investigations in this direction, however, nothing has been published. The apparatus constructed by Dieckmann (348) for an entirely different purpose and with dimensions much too small for the practice of earth investigations, may, however, serve as an example of the use of loop antennae for transmitting purposes. His apparatus was used for locating buried cables and the like.

The electromagnetic waves emanating from such a sender extend with the velocity of light. In vacua, the velocity of light is $3 \cdot 10^{10}$ cm. per second. In material-filled space, the velocity of propagation v, and thus also the wave length λ, is inversely proportional to the square root of the dielectric constant ϵ, if one excludes magnetic insulators, which are seldom present in the earth.

At every observation point through which the electromagnetic waves are drawn they are characterized by an electrical alternating field and a magnetic one at right angles thereto. The direction of both vibrations is at right angles to the direction of

propagation of the waves. If the waves go out from a linear antenna, then in the median plane the vibration direction of the electrical field lies parallel to the direction of the antenna, while that of the magnetic field is perpendicular to the plane laid through the point of observation and the antenna direction. In a completely homogeneous medium, the electrical and magnetic vectors of the electromagnetic radiation field would everywhere perform linear vibrations. However, in an inhomogeneous space, such as we practically always have in the problems of earth investigation, interference along wave paths running in different ways appears at the observation point because of refraction or reflection of the waves, and we again obtain elliptical polarized electrical or magnetic vectoral fields on which Ambronn first reported.

As receivers for the measurement of the properties of the incoming electromagnetic waves, the same apparatus is used as is employed in ordinary wireless telegraphy. In the older investigations using this method, on which there are reports in numerous papers by Leimbach (932, 936), Löwy (984), Löwy and Leimbach (986), Ambronn (23, 25, 27), Förstmann (472), Duschwitz (369) the receiver consisted of a linear antenna tuned to the frequency of the incoming waves together with a detector (usually a crystal detector) and a galvanometer. In modern measurements, a loop antenna is generally used. This permits a determination not only of the signal strength, but also of the plane of vibration and vibration form of the electric waves arriving at the place of reception. These loop antennae R (about 60 : 60 cm.) (Fig. 65) are freely adjustable in space, and the position of their plane is determined by compass and plumb line. Tuning is accomplished by means of the condensor C, and possibly also by means of additional coils S. High- and low-frequency amplifiers H and N are used for amplifying the oscillations in the loop antennae, which in themselves are weak. For the determination of direction, observation by means of the telephone suffices. For the measurement of the intensity and the vibration form of the incoming waves, either the last tube is used as a rectifier, or a crystal detector Gl is arranged with an output transformer, and the received current, thus amplified and rectified, is measured with the galvanometer.

The electric waves can be propagated only in non-conductors. They do not penetrate conductors of electric current, but are

reflected at their boundaries, for such reflection exactly the same laws holding as for light rays in optics.

The imperviousness of electrically conducting masses, such as water-bearing formations and many ore deposits, has led to numerous proposals for the practical application of the electrodynamic methods. The measurements refer either to the testing of the penetrability of the formations between sender and receiver of the electric waves arranged in bore-holes, in mining plants, or on the opposite flanks of a mountain to be penetrated by waves (Fig. 66), according to the Leimbach-Löwy method (937), or according to the scarcely feasible proposal of the simultaneous use of two senders by Rawen (1272), or in investigations on the electric waves reflected by conducting masses, or bent at their boundaries. The oldest proposal on reflection of electric waves in conducting masses for the detection of their spatial position is due to Hülsmeyer (749). The application

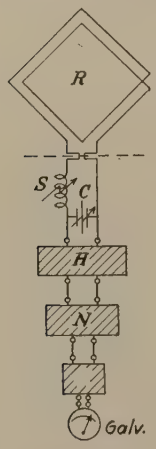


Fig. 65.

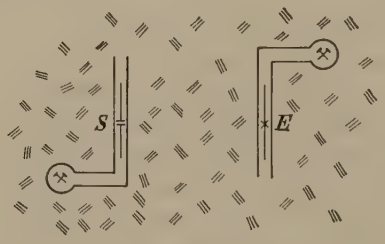


Fig. 66.

of this principle to the delineation of conducting ores was suggested by Trüstedt (1551). The methods of Löwy and Leimbach (984, 986) were, however, the first that could bring practical results, on which there are exhaustive reports by these two investigators (932, 936, 984, 986), as well as by Ambronn (24–29). In these reflection methods, either a receiver (986), screened from the rays coming immediately from the sender, is used for determining the reflected radiation, or the interference of the reflected rays with the rays coming immediately from the sender (Fig. 67) is measured for the various wave lengths used and for various positions of the sending or receiving place (984). The artificial methods of Machts (1019) and Rawen (1272) may be made worthless by practical difficulties. According to Ambronn (28), a convenient arrangement is often obtained by

arranging the sending and receiving stations (Fig. 68) so that the energy transmitted in the direct line between them is at a minimum; then, by placing the two stations rather close together one can use energy which is almost vertically incident to the reflecting formation. Theoretically, this condition is the most simple and gives the maximum energy in the reflected wave.

The efficiency of the special case of perpendicular reflection, in which the electric waves return to the transmitter itself and thus influence the oscillations in it, according to Leimbach (933), may not, in general, be convenient in practice, because of the small energy in the returning waves.

The introduction of the loop antenna into the technique of wireless telegraphy disclosed the possibility of exactly determining the intensity, the direction, and the plane of polarization of

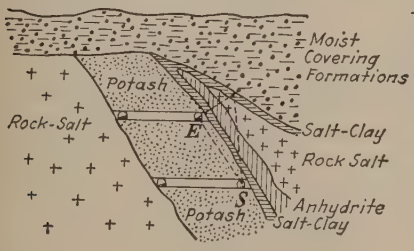


Fig. 67.

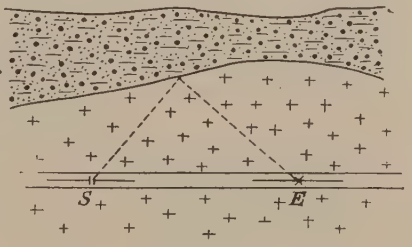


Fig. 68.

the incoming waves, which though theoretically possible with linear antennae, was practically scarcely feasible. The Gesellschaft für Drahtlose Telegraphie (536) and Ambronn (407, 408) have indicated methods of determining the direction of the radiation by means of loop antennae. Ambronn (408) shows how one may, by the use of several transmitting antennae crossing one another, determine the actual ray direction at the transmitting place by means of the loop antenna at the receiving place. This position is found through a simple measurement, as only one plane is to be determined. He uses, further (407), the possibility of the exact determination of the direction of the electromagnetic waves arriving at the receiver for investigation of bending phenomena in conducting bodies or in deposits of irregular dielectric constant, possibilities which Schilowsky (1363) has already tried to use, but with entirely inadequate apparatus. Hancock (637*a*) wished to establish through such directional measurements the direction for driving drifts in

mining work, but clearly underrated the electrical inhomogeneity of the normal formations, which completely distorts the surfaces of the waves coming out of the formation at the receiving position, if the wave energy has not already been absorbed in the formation because of its conductivity.

More original than practically feasible, proposals for earth investigations by means of electrical waves from a flying machine or airship have recently been brought out by Löwy (984, 985) (see also Berg (168*a*)).

Investigation of the wave form of electric waves reflected from conducting formations may serve for obtaining information of the magnitude of the electrical conductivity of the reflecting formation. A method of this kind was proposed by Ambronn in order to obtain, from the kind of reflection of electric waves obtained from the ground-water formation in desert regions, a decision concerning its salt content, which is of prime importance in the economic utilization of such ground water sources. Theoretical bases for the performance of practical investigations according to this method have been prepared by Hellwig (686).

With the electrodynamic methods, it is often difficult to excite oscillations in antennae which are buried in borings placed in dry formations, but which are surrounded by a moist formation. According to Leimbach (416, 419) one can overcome this difficulty by using, instead of the fundamental vibration of the antennae structure, a harmonic which has a potential node at the place where the antennae system penetrates the conducting formation. Leimbach (934) also proposed an insulation of the antenna from damp formations by freezing out the latter around the place of penetration.

To the electrodynamic methods of investigation belong those methods in which the electrodynamic properties of an electrical oscillation system placed at the surface of the earth or sunk in the subsoil, are influenced by electric constants of the objects buried in the soil. The capacity of an antenna buried in a bore-hole is dependent upon the dielectric constant of the vicinity (Leimbach and Meyer (937*a*)). If one measures the capacity of the antenna by inserting the same in an electric oscillation system, then one can determine the dielectric constants of the formations surrounding the bore-hole. Thus, for example, according to Löwy (984) one can determine whether, during the steplike lowering of the antenna in the boring, the capacity

changes suddenly because of the boring penetrating a formation of other dielectric constant. With the approach of such an antenna to conducting masses (for instance, lye accumulations in potash mines) vortical currents are excited in them, which consume energy and thus effect an additional damping in the vibration system to which the antenna belongs. Leimbach (418) used similar methods for establishing the course of borings and for investigating the frost wall of a frozen shaft (935).

The Gesellschaft für Praktische Geophysik (537) wishes to use the change of the capacity of a drill pipe which serves for opening an oil deposit, due to the approach of water which presses on the oil flowing toward the well. As long, however, as the effect of the numerous other accidental factors is not constant, they will influence a drilling column standing in the ground for its entire length without insulation. Hence, the proposed mode of action for especially sharp determination of the apparent capacity of such an insufficiently insulated tube may scarcely be suitable for examining the desired water approach.

A method with use of a loop antenna as an oscillation system is used by the Gesellschaft für Drahtlose Telegraphie (535) for seeking out conducting bodies lying buried. Lower frequencies are used apparently by the "Alpha" apparatus (22) according to de Nerville (886), depending upon the changes of the mutual inductance of flat coils with the approach to conducting or magnetic bodies. A contrivance devised by Conklin (314, 382, 886) consists of a circular wire loop laid on the soil, in which are produced high-frequency electric oscillations whose magnetic field one surveys in the interior of the loop surface. This field is examined by using two exploring coils having the same diameter and connected in series opposition through a detector to a galvanometer. With one coil held stationary, the other is moved along a curve in such a way that the galvanometer reading remains at zero. Over homogeneous subsoil, these curves are circles. Inhomogeneities of the electrical conductivity produce deviations from this normal form. In practice, however, this very crude method may hardly be approved.

On the other hand, the technique of wireless telegraphy may be of importance to geophysics and geology. In the radio-transmitting sending stations one is accustomed in many cases to use the earth itself as a counterpoise, so that the potential modes of the sending antenna system coincide with the upper

boundary of the ground-water formation, which conducts well. Thus the spatial distribution of the electrical conductivity and its absolute value produces an influence on the oscillations in the transmitting system, especially on the resistance of the antenna system, on which exhaustive researches have been instituted by Reich (1289*f*), Abraham (4), Austin (74, 75), Meissner (1070), Lübben (987). A comprehensive exposition of the relations, especially complicated in artificial earth, with especial regard for the geologic questions thereby drawn into consideration, is given by Pfalz (1233).

Relative to a systematic inversion of these relations, in order to draw inferences on the electrical distribution in the conducting subsoil and its geologic structure from the properties of grounded and ungrounded antenna systems, nothing is known up to the present.

In the radiation of electromagnetic waves from a transmitting station, the alternating current supplementing the electromagnetic oscillations in the air also attains a high value on the surface of the earth. The electromagnetic waves adhere, so to speak, to the surface of the earth, and the connection seems to be so much the stronger the higher the conductivity of the uppermost earth formation. The conditions for the transmission of the electric waves are most favorable over the sea with its well-conducting salt water. The transmission between stations which are separated from one another by the sea is therefore much better than between stations similarly distant from each other but between which land masses extend. The important properties of the transmission of electric waves along the surface of the earth, have been exhaustively treated by Zenneck (1662), Sommerfeldt (1465), Reich (1289*f*), Görnemann (573), Macdonald (1011), Erskine-Murray (428), Eckersley (380), Nichols and Schelleng (1163), Larmor (909*a*), Appleton (53*a*), Ollendorff (1196*b*), Kiebitz (805*c*), and others. Busch (280) experimentally investigated the earth currents in the vicinity of a transmitting apparatus, on whose development True (1550) also reports, while Demmler (346) measures the velocity of propagation of electric waves on the surface of the earth.

When the soil conditions are not uniform on all sides of the transmitter, the wave surfaces and radiation directions of the transmitted electric waves are differently influenced in different directions, so that the intensity of the radiation in different

directions or for definite receiving regions can vary from the normal values. Similarly, the directions from which the incoming waves appear to come at the receiving place are disturbed (see Eckersley (380*c*)). These disturbances are almost equally great for all wave lengths if the waves reach the receiver on a uniform path, being disturbed only by soil conditions of the irradiated region (1046). According to Austin (80), the vertical angles of the wave surfaces also are disturbed.

In other cases, however, the waves plainly take different paths from the transmitter to the receiver and interfere there with one another, as has been thoroughly investigated by Heiligtag (679). In this case, the deviations (differences between the true observed directions and the direction calculated from the geographic relation of the stations) are dependent upon the wave lengths used. Although these relations have already been treated in numerous investigations, among others by Ludewig (989), Mesny (1089), Pickard (1236), Hullen (748*b*), Brammer (233*b*), Smith-Rose (1457*a*), an application to the problems of applied geophysics has not yet followed. How strongly the condition of the surface of the earth can influence the receiving relations of electric waves within very small regions is shown by Lardry (908) and Bäumler (137). A more exhaustive treatment of the problem of the propagation of electric waves along the surface of the earth is also found in Mathias (1054, p. 389 *et seq.*).

Besides the temporally invariable conditions of the abnormal propagation of electric waves which may arise from the conductivity relations of the uppermost earth formations, a great number of processes take place in the atmosphere which have in attendance temporal changes of the signal strength and radiation direction at the receiving stations. These diurnal variations in the condition of the so-called Heaviside-layer, a conducting layer ionized by the sun's rays and therefore reflecting the electric waves, and assumed to be about 100 km. in height, shall not be gone into here, since the problems of applied geophysics do not seem to be concerned with these processes. Besides the general expositions already mentioned, data thereon are found in Stoye (1489), Austin (78), Elias (383), Reich (1289*f*), Koertz (845), Marconi (1044), Appleton and Barnett (54), Barfield (95), Gockel (565), Breit and Tuve (244), Eccles (379*a*), Meissner (1071), Lassen (919*a*), Eckersley (380 *a*, *b*), Hulburt (748*a*),

Russell (1332*a*) (also 613*d*, p. 415 *et seq.*). Breit (243) investigates the influence of the magnetic field of the earth on the propagation of the waves. An explanation of the daily fluctuations of the received energy as due to precipitation of radioactive products and the sun's radiation, as Iljin (764) would assume, is improbable; otherwise this phenomenon also would be treated fully in our models.

Of some significance, however, for practical geophysical purposes, are the short periodic variations (fading effect), the directional changes of the incoming waves, and the manifold crackling, hissing, and rustling disturbance noises. For these phenomena depend upon the meteorological and electrical condition of the atmosphere, which can be influenced also by the properties of the uppermost earth formations in manifold ways. A comprehensive editing of the questions belonging here is given by Ludewig (989) (see also Bäumler (137*a*)); meanwhile, however, many new points of view have sprung up. Koertz (845) has worked up a great part of the observations coming into consideration. Further mention should be made of the work of Dieckmann (349), Austin (76, 77, 79), Wiedenhoff (1618), Rothé (1305), Lacoste (888), Breit (243), Colwell (311), Watt (1585), Dellinger and Whittemore (345), Duckert (362*a*), Lejay (930*a*). Relative to the connections of the receiving disturbances with meteorological processes, although here coming less into consideration, reference is made to the publications of Bellini (155), Stoye (1489), Wolf (1642*a*), Rothé (1305), Bureau (273), Mathias (1054, p. 429 *et seq.*), Herath (709), Bigourdan (186), Austin (79), and others.

On the connection of these phenomena with the structure of the subsoil, scarcely anything accurate is known. Atmospheric disturbances should appear simultaneously at all observation points, according to Bäumler (136), and are therefore independent of the subsoil. On the other hand, according to Kinsley (808), signal-strength fluctuations and abberations exhibit local effects. An observation of Watt and Appleton (1586) appears noteworthy here, that in the appearance of periodic disturbances, in seven out of eight cases, negative electricity flowed into the earth. Of practical importance, also, are the observations of Austin (76), Watt (1585), Hubert (747*a*) (also Schindelhauer (1364)), that the directions from which the great

sudden disturbances (crackling, etc.) come, are not distributed at random, but always proceed from the direction of isolated mountains, high mountain ranges, and the like, but almost never from the sea. Schindelhauer (1364) finds some kinds of disturbances which come in directions frequetly coinciding with the direction of the magnetic meridian (see also 613 d. p. 425).

CHAPTER VII

THE INVESTIGATION OF THE STRUCTURE OF THE SUBSOIL BY MEANS OF ELASTIC (SEISMIC) WAVES

The Fundamental Physical Principles of Seismic Soil Investigation.—The broad physical principles on which seismic subsurface investigation is based can be only briefly treated here. The mathematical development of the theory of elasticity will be omitted. For the mathematical treatment reference is made to the literature, for instance, to the section on the theory of earthquake waves by Gutenberg in Sieberg's "Erdbebenkunde" (1443, p. 283 *et seq.*, also 613*d*, p. 240 *et seq.*), which gives a short discussion of the introduction of the theory of elasticity into the investigation of earthquake phenomena by Gay Lussac (522), who compared the earthquake waves to sound waves in air. Gutenberg also shows how Mallet (1039) recognized the occurrence of transverse waves in the solid crust of the earth, and how numerous investigators, using the improved earthquake data for the study of the propagation of the earthquake waves in the body of the earth, have perfected methods up to the work of Wiechert (1606, 1612). From the year 1899, he laid the foundations, and, with his numerous students, developed those ideas and theories which today form the basis of the science of seismology.

The propagation of elastic waves in the earth is dependent upon the elastic properties of its constituent materials. Elastic waves in air and water may be designated as sound waves, elastic waves in the rigid mass of the earth as seismic waves. In air and water, only longitudinal or compressional waves can develop, in which each element of the medium swings back and forth about its position of rest along a path parallel to the direction of propagation of the wave. The velocity u_g of the propagation of these waves is dependent in air upon pressure p, density ρ, and the relations of specific heat at constant pressure or constant volume $\varkappa$ in the form

$$ug = \sqrt{\varkappa \cdot \frac{p}{\rho}}$$

In fluid bodies, the velocity depends upon the compressibility k, instead of pressure, so that the velocity of sound in fluids is given by the relation

$$u_{fl} = \sqrt{\frac{k}{\rho}}.$$

In rigid bodies, however, the relations are very much more complicated:

If a rod 1 sq. mm. in diameter is stretched by pulling, the ratio E of the load in kilograms to the extension per centimeter of the length of the rod caused thereby, according to Young, is designated as the modulus of linear extension (called Young's modulus). The elastic stretching of a rod under tension is accompanied by contraction in its cross-sectional dimension. The ratio of the extension to the decrease in diameter of the rod is called Poisson's constant σ which for various rigid substances lies between 0.2 and 0.5. Together with the density ρ, the two elastic constants E and σ determine the rate of propagation of elastic waves in a homogeneous rigid body.

Besides the above constants which are used in the general theory of elasticity, in seismology, Lame's coefficients λ and μ are conveniently made use of. The latter μ, designated as the modulus of rigidity, possesses a very practical and clear significance in the characterization of the elastic properties of the individual constituents of the body of the earth.

The relations between the constants E and σ and the coefficients λ and μ are given by the following equations:

$$\lambda = \frac{\sigma}{(1+\sigma)(1-2\sigma)} \cdot E; \quad \mu = \frac{1}{2}\frac{E}{1+\sigma};$$

$$\sigma = \frac{1}{2}\frac{1}{\lambda+\mu}; \quad E = \frac{\mu}{\lambda+\mu}(3\lambda + 2\mu).$$

If elastic waves are produced by a disturbance of the equilibrium in the interior of a solid body, besides the longitudinal waves which travel with the velocity V, there will be produced transverse (shearing) waves, which cause the material particles to vibrate perpendicularly to the direction of propagation of the waves, and which travel with the velocity v when

$$V = \sqrt{\frac{\lambda+2\mu}{\sigma}} = \sqrt{\frac{E}{\rho}\frac{1-\sigma}{(1+\sigma)(1-2\sigma)}},$$

$$v = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{\rho}\frac{1}{2(1-\sigma)}}.$$

If only central forces operate between the molecules of the material in question, according to the theory δ will equal $\frac{1}{4}$, and thus $V/v = \sqrt{3} = 1.732$.

Conversely, as is important for the application of seismology to practical earth investigations, one can determine from the measured velocities V and v the elastic properties and the density of the subsurface formations penetrated by the vibrating waves. For the determination of the three constants E, ρ and σ or λ, μ, and ρ, however, only two equations are present, so that for the attaining of an unequivocal result one must seek still a third relation or must make suitable supplementary assumptions.

When the waves encounter a boundary between two solid bodies which have different elastic properties, a part of the wave energy is reflected, and a part enters the second medium as refracted waves. For each longitudinal and transverse wave which encounters the boundary, there is produced a refracted and reflected wave of each kind, so that a very complicated condition of motion prevails (see, for instance, Zoeppritz (1667)). The distribution of the energy content of the incident rays between the reflected and refracted rays is treated by Jeffreys (762*g*). In addition to these two types of waves, several types of surface waves are produced (see Stonely (1488), Visser (1567)). The most important of these surface waves are the so-called Rayleigh waves (Lord Rayleigh (1275), Lamb (896), Wiechert (1612,) Uller (1556), Nakano (1151*b*)), which are built up of the total effect of the longitudinal and transverse waves at the bounding surface and are propagated along the surface of the earth with a velocity.

$$\sqrt{V_L} = 0.9194 \sqrt{\frac{\mu}{\rho}} = 0.9194v.$$

Also surface waves are generated (Love waves 981, 982) in which the particles vibrate perpendicular to the direction of propagation of the waves and which are associated with individual vibrations of the uppermost ground formations. Along the bounding surface between two formations with different elastic properties, surface waves of different types are generated which play a very important role in the practice of seismic earth investigation. But besides the investigations of Jeffreys (762*f*) on a kind of transverse surface wave at such a bounding surface, which travels with a velocity equal to that of the longitudinal wave in the medium

with the greater wave velocity, up to the present nothing is known theoretically on the kind of surface waves within bounding formations. For a complete presentation of the physical principles of seismology reference should be made to the exhaustive treatment of the physical phenomena and mathematical theories in the textbooks and handbooks of Mallet (1040), Hoernes (729), Hadamar (621), Burkhardt (274), Tedone (1520), Müller and Timpe (1144), Knott (821), Hobbs and Ruska (725), Rudzki (1326), Galitzin (514), Inglada (767), Mainka (1036), Sieberg (1443), Conrad (316), Rothé (1306*a*), Gutenberg (613*d*). In these investigations the body in which the elastic waves are propagated is usually considered as isotropic; that is the elastic properties, and with them also the speeds of propagation of the elastic waves, are assumed as independent of the direction of propagation of the waves. In anisotropic masses, in which this condition is not fulfilled, the propagation of the elastic waves is very complicated. Rudzki (1324, 1327, 1328, 1328*a*) offers an introduction to the problem of wave propagation in anisotropic bodies.

In order to draw conclusions as to the physical character of the formations traversed by seismic waves from the values for the elastic constants derived from seismic observations, one must establish experimentally the elastic constants for a sufficient number of rock types. Such determinations have been carried out, partly in the laboratory on rock samples, partly on natural occurrences in the field, by Mallet (1041), Nagaoka (1151), Kusakabe (881, 882, 883), Oddone (1191); the elastic properties of some minerals have been studied relatively by Fouqué and Lévy (473), Noguès (1183), Milne (1106), Hess (714), Johannsen and Phemister (771) (see also Andrews 39*b*). Since, however, the present methods of measurement for making these researches are rather unsatisfactory, a description of the methods will not be given here. The values of the elastic constants given in the literature vary considerably for rocks which are apparently similar, especially if the elastic constants have been determined by different methods. Temperature and pressure have a very pronounced effect upon the elastic properties of materials (see for instance Kusakabe 885). With sufficiently high pressure even plastic deformation can occur, as for instance Adams (8) and King (807) show for limestone. Adams and Coker (8*a*) have reported on the relation of the elastic constants of rocks to

their compressibility. Also the size of the deformation which excites the waves at their place of emanation seems to affect the electric properties, according to Kusakabe (881). Average values for the speed of propagation of longitudinal and transverse waves in rocks, arranged first according to the kind of rock and then according to the geologic age, is given in Table XVI, after Sieberg (1443, p. 172). The values are valid for the temperature and pressure relations normally present in the uppermost earth formations.

TABLE XVI.—SPEED OF PROPAGATION OF EARTHQUAKE WAVES FOR DIFFERENT ROCKS

Designation	Speeds of propagation in kilometers per second					
	Longitudinal waves			Transverse waves		
	Aver.	Max.	Min.	Aver.	Max.	Min.
Kinds of rock:						
Crystalline schist	6.3	7.0	5.5	3.1	3.3	2.8
Plutonic rock	5.3	8.0	2.1	3.2	4.7	1.3
Effusive rock	2.8	4.2	1.4	1.9	2.7	0.8
Sedimentary rock in general	3.6	5.9	1.2	2.0	3.4	0.8
Limestone	5.0	5.7	3.8	3.0	3.4	2.4
Sandstone	1.8	2.2	1.4	1.1	1.4	0.8
Geologic age of the rock:						
Archaeozoic	5.6	7.0	4.1	2.9	3.3	2.5
Paleozoic in general	5.2	8.8	2.1	3.0	5.4	1.3
Paleozoic sedimentary	4.5	5.7	2.2	2.5	3.4	1.4
Mesozoic in general	3.4	5.9	1.8	1.9	3.9	1.0
Mesozoic sedimentary	3.4	5.9	1.8	1.9	2.9	1.0
Tertiary in general	2.4	3.2	1.2	1.7	2.5	0.9
Tertiary sedimentary	2.1	3.0	1.2	1.4	2.0	0.9
Quaternary in general	2.5	3.6	1.4	1.6	2.2	0.8
Quaternary sedimentary	2.2	3.6	1.4	1.3	2.2	0.8

For the practical application of the seismic methods, however, these values are usable only in very limited degree. Experience in the field has shown that laboratory measurements on the hand specimen may yield results entirely different from the velocities observed in great rock masses in their natural position. Practice has shown that the velocity of sound is entirely independent of the geologic age of a rock and depends on its petrographic charac-

ter alone. The seismic methods of subsurface investigation serve therefore also for the investigation of the geologic and tectonic structure of the subsoil by determining the petrographic character of the different subsurface formations.

Although our exposition of applied geophysics will concern itself with the physical exploration of the uppermost earth formations, the methods of scientific seismology which concern the entire body of the earth will be treated here, because conclusions may be drawn from these methods and instrumental aids used in them which can be employed for the exploration of the uppermost earth formations. (Special publications on the seismic methods of earth investigation of applied geophysics are almost completely lacking.) Moreover, from the characteristics of local effects which are observed in the investigation of the structure of the entire earth's body, conclusions can be drawn as to the structure of the crust of the earth in earthquake regions themselves or in the immediate vicinity of the place of observation.

The elastic constants and wave velocities assembled above refer to homogeneous masses of the rock materials concerned. The body of the earth, however, as seismic investigations have shown, exhibits a very complicated structure. Although it is constructed of a number of concentric spherical shells with increasing density toward the interior and with different elastic characteristics, the individual formations may be considered as almost homogeneous and isotrophic in themselves. On account of the smallness of their dimensions in contrast to the wave lengths of the seismic waves in the uppermost crust of the earth, the individual crystalline elements need not be considered.

The Formational Structure of the Interior of the Earth.—If at any place in the crust of the earth a strong earth vibration, such as an earthquake, is released, then in a completely homogeneous earth sphere the waves would travel with always the same velocity. The rays of seismic energy would make straight lines, chords, and the time which elapsed up to the appearance of the waves at a place of observation would be proportional to the length of this chord. The observations on the propagation of the vibratory waves emanating from very strong earthquakes, however, show entirely different regularities. From the differences of time between the occurrences of a great number of earthquakes and the appearance of their respective waves at the

different places of observation, the so-called time-distance curve is produced, and tables have been made which show the dependence of the running-time upon the distance of the observation place from the epicentrum of the quake. The epicentrum of a quake is that place on the surface of the earth which lies directly above the real quake focus in the subsurface (the hypocentrum). The distance is given along the great circle and is generally expressed in angular degrees. These tables, which are designated as time-distance tables, and the graphic expositions, which are designated as time-distance curves, form the most important means of interpretation in seismic investigations and also are of fundamental importance in seismic methods of applied geophysics.

From every point of disturbance (from every earthquake center), elastic wave trains of different types emanate with different velocities; for each type of wave train one can deduce special time-distance curves. Also for the waves reflected at the boundary between two formations with different elastic properties and for the different surface waves such time-distance curves can be deduced. We will limit ourselves here to the observation of the direct (perhaps we will consider also waves refracted at formation boundaries) longitudinal, transverse, and surface waves. While in seismic investigations of the earth's body reflected waves also play a great role, these seem to be without essential importance for seismic subsurface investigations. Up to the present, reliable observations on their appearance with explosion waves are lacking. With magnification of earth movements up to 100 million, disturbances in seismograms which could be classified as reflected waves with certainty have not been found up to the present by Ambronn. The data of Hubert (747), Brand (235*a*), Mothes (1137*a*), and others are to be taken with caution, since the seismogram can be given several different interpretations.

As an example of the movement of the surface of the earth by the passage of the different kinds of elastic subsurface waves produced by an earthquake, in Fig. 69 is shown schematically the seismogram of a quake (epicentral distance about 2,500 km.) in which only the basic types of waves designated above are noted. The longitudinal waves which have the greatest velocity produce the first movement, designated by *P* (primae undae) (see von dem Borne (207)), in the formerly only weakly restless wavelike designation of the seismographs. To an initial sharp break,

as is here assumed, an i (impetus) is added. A gradual growth of the ground movement is designated by e (emersio). After the passage of the P-waves, the curve becomes more irregular, and after about 3½ minutes will be interrupted by the arrival of the first transverse wave trains S (secundae undae). These are followed in about 2½ min. by the first surface waves L (longae undae), with increasing amplitude. In the course of the next minutes, the L waves merge into the M-waves (maximae undae), which continue with gradually decreasing amplitude, and finally cease.

Time-distance curves and tables, derived from increasingly comprehensive and more reliable data, and with an improving theoretical insight into the actual relations, have been deduced by J. Milne (1114), Wiechert and Zoeppritz (1612), Zoeppritz, Geiger and Gutenberg (1668), Wegener (1593), Hecker (670),

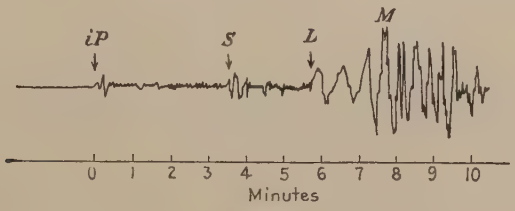


FIG. 69.

Gutenberg (598, 613*b*), Geiger and Gutenberg (524), Visser (1566), A. Mohorovicic (1124, 1126), S. Mohorovicic (1129), Meissner (1077*b*), Macelwane (1013*b*), and others. Complete tables are given by Zeissig (1659), Klotz (814), and Gutenberg (1443, p. 288 *et seq.*) in Sieberg's Erdbebenkunde as well as in his textbook (613*d*, p. 243 *et seq.*). Lutz (1008*a*) sought to show the characteristics of the local subsurface by deducing time-distance curves for each locality.

On the basis of the observational results collected in these tables to date, one may represent the structure of the earth's body somewhat as follows:

The earth consists of a spherical core (apart from the flattening due to rotation) on which are deposited spherical shells of varying material composition. According to Gutenberg (603, see also 613*d*, p. 263), the following are the most accurate data available from the observations on the propagation of earthquake waves, for the depth of the bounding formation between the individual

shells, for the velocity V of the longitudinal and the velocity v of the transverse waves, for the density ρ and for the rigidity coefficient μ of the successive formations:

TABLE XVII

Depth kilometers	Designation	V kilometers per second	v kilometers per second	ρ	μ centimeters^2 second$^{-2}10^{11}$
0	Surface of the Earth	5.6 ± 0.15	$3\frac{1}{2} \pm \frac{1}{2}$	2.8	$3\frac{1}{2}$
60 above	Mantle	5.9 ± 0.2	$3\frac{3}{4} \pm \frac{1}{2}$	3	$4\frac{1}{4}$
60 below	Barysphere	8.0 ± 0.1	4.3 ± 0.2	$3\frac{1}{2}$	$6\frac{1}{2}$
1,200	.....	$12\frac{1}{2} \pm \frac{1}{2}$	$7 \pm \frac{1}{2}$	$4\frac{3}{4}$	23
1,700	Intermediate	$12\frac{3}{4} \pm \frac{1}{2}$	$7\frac{1}{4} \pm \frac{1}{2}$	$4\frac{3}{4}$	25
2,450	Formations	$13\frac{1}{4} \pm \frac{1}{2}$	$7\frac{1}{2} \pm \frac{1}{2}$	$4\frac{3}{4}$	26
2,900 above	.....	$13 \pm \frac{1}{2}$	$7\frac{1}{4} \pm \frac{1}{2}$	4.9	25
2,900 below	.....	$8\frac{1}{2} \pm \frac{1}{2}$	5 (?)	11	27
5,000	Core	11 ± 1	$6\frac{1}{4}$ Uncertain	11	36
6,370				11	43

Further classifications of the boundaries of the individual spherical shells and their physical properties which agree more or less with the above data are found in Milne (1114), Zoeppritz and Geiger (1667*a*), Benndorf (160*a*), Inglada (766), Gutenberg (602), Angenheister (47, 51*c*), Tams (1511), S. Mohorovicic (1129), Macelwane (1013); Gutenberg (610, 611, 613) considers especially the elastic structure of the upper earth formations. Haalck (614) extends the investigations by correlation with gravitational effects, while Rösch (1299) turns especially to the physicochemical conditions in the interior of an earth built up of such concentric formations. Gutenberg (613*a*) also considers the question to what depth the earth is crystalline.

The propagation of longitudinal waves in an earth so constructed is shown in Fig. 70, according to Gutenberg (1443, p. 399) with the omission of reflections. The wave surfaces belonging thereto are shown by broken lines. The minute numbers give the running time. The construction shows that from an epicentral distance of about 105° the P-wave decreases rapidly in intensity, so that as an epicentral distance of 140° is approached, the P-wave completely vanishes. On the other hand, there is found at an epicentral distance of about 142° a kind of focal point for those longitudinal waves which have penetrated the core, in which the wave velocity is notably smaller than in the outer shell. The time-distance curve belonging to this

schematic exposition is given in Fig. 71, in which the recurrent branch of the upper portion has been omitted. Similar relations exist for the transverse waves, with the difference that transverse

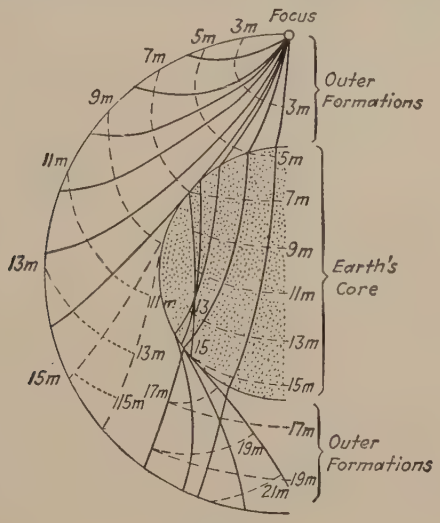


Fig. 70.

waves which have passed through the core have not as yet been observed (see also Gutenberg (613*b*), Jeffreys (762*d*)).

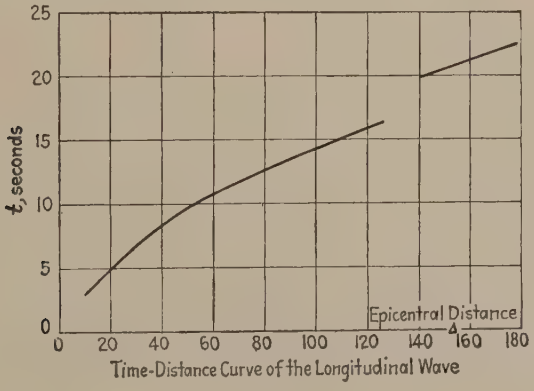


Fig. 71.

The depth to which an earthquake ray penetrates the earth is designated as the vertical depth. For the calculation of this depth, as well as the variation of velocity as a function of depth, compare Wiechert and Geiger (1616).

Figure 70 also shows the angle (angle of emergence) at which the longitudinal earthquake waves appear at the surface of the earth, and the dependence of this angle upon the epicentral distance. For the magnitude of the angle of emergence, however, different values result from different methods of determination. If one derives the angle of emergence from the time-distance curve, as in Fig. 70, one obtains the true angle of emergence. If one calculates it from the direction of the displacement of a point on the surface of the earth, then this apparent emergence angle differs from the true emergence angle, since the incident longitudinal waves of the bounding surface are reflected as longitudinal and transverse vibrations with different reflection angles. In the case of transverse waves, the position of its polarization plane, as well as the form and position of its vibration ellipse, have to be considered.

After Wiechert (1612) had pointed out these relations of the different angles of emergence, Benndorf (162), Zoeppritz (1667), and Wilip (1627) sought to utilize them further for the analysis of the structure of the earth. In regard to the geologic structure of the uppermost earth formations, the works of Benndorf (165, 166) are of especial interest. He shows how, from the velocity of the advance of the first impulse of the longitudinal earthquake waves along the surface of the earth, and from the apparent angle of emergence, the actual speed of propagation of the transverse waves in the vicinity of the earthquake can be determined. In these papers, Benndorf showed, probably for the first time, "the possibility of determining directly the existing geologic differences in structure of the outermost crust of the earth by means of seismic observations." Galitzin (505) also emphasizes the importance of the observation of the direction of vibration of a portion of the ground with the passage of the two advance waves for the same purpose, especially for small epicentral distances (see also 516*a*). Practical applications of this method have not been made, however. Mainka (1034) refers to the influence of the geologic condition at the recording station on the relation of the two emergence angles and shows how one can derive from this relation Poisson's constant for the rock masses lying under the recording station. He obtains the value $\sigma = 0.376 \pm 0.032$ for the formation beneath the Göttingen earthquake observatory from 9 quakes, and for the Pulkovo station $\sigma = 0.296 \pm 0.022$ from 17 quakes. With the apparatus

used up to the present for observing artificially produced vibrations in the subsurface for geologic purposes, however, much too little has been accomplished in the way of quantitative determinations of amplitude. Schweydar and Reich (1425*b*), however, show that the apparent emergence angle of the short elastic waves produced by an explosion at a very short distance from the point of origin ($\angle 100^m$) amounts to almost 90°; the longitudinal waves thus come almost vertically from below to the surface of the earth.

The detection of the deflection of the plumb line with the passage of earthquake waves has been vainly attempted by Schlüter (1371) by means of his klinograph, by Galitzin (514) with the double pendulum, by Angenheister (44) by observation of the stars in the telescope; on the other hand, on the occasion of the great explosion at Stade (about 1860) a jerking of short duration was perceived in by an observer, at the Göttingen astronomical observatory, where the polar star was accidentally being observed in meridian. That this observation is at variance with the other investigations above may perhaps be due to the fact that explosion waves have a much smaller wave length than normal earthquake waves. So far the occurrence of torsional movements has not been definitely established (*cf.* Heritsch and Schwinner (713), Schmidt and Mack (1395), and Oldham (1195), for further discussion).

The Generation of the Elastic Subsurface Waves.—The generation of elastic waves in the subsurface can occur either from natural causes, uninfluenced in place, extent, strength, and time by man's will, in the form of earthquakes, or artificially and intentionally by explosions, by the fall of weights, by means of a revolving mass periodically agitated, or by means of mechanical oscillators placed beneath the surface.

Under the natural processes, earthquakes produced by sudden releases of internal stresses in the brittle skin of the earth with formation of fractures, faults, folds, and the like, or sudden dislocations in tectonic disturbance zones already present (dislocation quakes) form the most important group. Earthquakes are produced also by subterranean collapses of caverns, and by volcanic disturbances (*cf.* 1443, p. 178 *et seq.*). The perceptible vibrations or the disturbances caused by earthquakes are usually strongest in the vicinity of the epicentrum. Isoseists are lines which connect places of equal intensity of quake effect on the

surface of the earth. The quake intensity is appraised either according to the perceptibility or the damage arising from it according to Mercalli (1082), Tams (1510, 1258, p. 295 *et seq.*), Sieberg (1443, p. 98 *et seq.*), Inglada (765*a*), for sea quakes a corresponding scale has been established by Rudolph (1317), or according to Holden (735) absolutely according to the kinetic energy of the maximum quake movement. Cancani (283) compared the intensity of earthquakes according to the maximum acceleration of the ground segments. Galitzin (511) perfected instruments which were capable of measuring the acceleration. Table XVIII, after Tams (1258), gives a brief summary of the most important scales. The logarithms of the acceleration according to Cancani are about proportional to the Mercalli degrees.

TABLE XVIII

Mercalli degrees	Cancani	Effect at the surface of the earth
1	<2.5 mm./sec.^{2}	Only instrumentally noticeable
2 to 4	2.5 to 25	Very light to moderate
5 to 7	25 to 250	Rather strong to very strong
8 to 10	250 to 2,500	Destructive
11 to 12	2,500 to 10,000	Catastrophic

Davison (334) gives a compilation of 27 different older and newer earthquake scales (see also Sieberg, 613*d*, pp. 173 *et seq.*).

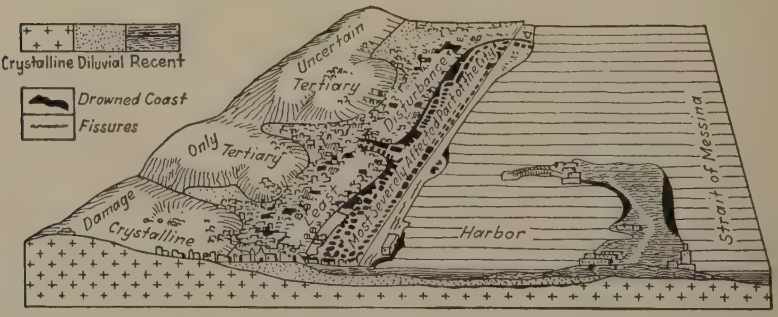


FIG. 72.

The isoseist map planned on the basis of these "macroseismic" observations can be employed for important conclusions on the geologic structure of the subsoil (see also Sieberg (613*d*, p. 180

et seq.)). Figure 72 shows a spatial exposition of the macroseismic effects of the Messina quake in 1908 according to Baratta (100) and Sieberg (1443, p. 108). One clearly recognizes here the generally established fact that the destructive effect is least in hard, especially crystalline, subsoil, while recent formations and loose water-soaked soil, because of the easier interior movement, and perhaps also because of the individual vibrations arising through resonance, suffer most damage. To a small degree the isoseist map of the earthquake of July 20, 1913, for the city of Freiburg, i. Br. by Lais (892; 1443, p. 493) illustrates the above very clearly. The same conclusion results from a comparison of the isoseists of the central European earthquake of November 16, 1911 (according to Lais and Sieberg (893); (1443, p. 107)), with the general geologic structure of the region. From a comparison of the disturbances in different formations in the great California earthquake of April 18, 1906, Reid (1291) obtained (see also Tams (1505*c*)) in comparison with rigid crystalline rock, in sandstone 1 to 2.4 times, loose sand 2.4 to 4.4 times, made ground 4.4 to 11.6 times, and marshy soil as much as 12 times the maximum displacement obtained in crystalline formations. Reich (1285, 1286) compares a number of German earthquake stations with Pulkovo (150 to 200 m. of plastic clay on Archaean) as a place of reference. He obtained the following basal coefficients: Hamburg (tillite) 0.7; Königsburg (sand and loam on rock) 1.1; Potsdam (compact sand) 1.2; Göttingen (limestone) 1.6; Upsala (crystalline rock) 1.7; Breslau (tillite over sand and gravel) 2.2. Further mention may be made of the investigations of Macelwane (1012) for the California quake of September 19, 1923, and the comprehensive exposition of Sieberg (1442). The reports of Schmidle (1373) on the effects of the earthquake of November 16, 1911, in Konstanz, likewise contain numerous references to the influence of the special character of the subsoil on the local quake intensity. Detailed compilations on subsurface coefficients for the different wave forms are given by Gutenberg (613*b*, pp. 75, 79, and 82).

The special tectonics of the subsoil also are of great importance. Faults, formation boundaries, and the like in the vicinity of the receiving stations can change the direction of the incoming waves and make the subsurface coefficients dependent upon the direction from which the waves come, as reported for the seismic station in Göttingen by Reich (1286).

The localizing of the earthquake center follows on the basis of the macroseismic observation from the assumption that the hypocentrum must lie under the most strongly disturbed epicentral region. In this, however, the stratographic composition of the subsoil also is to be considered. As an instructive example may be mentioned the study of the central European earthquake of November 16, 1911, and of Llarena (968*a*) by Lais and Sieberg (893). One can derive also the position of the epicentrum of a quake microseismically by means of the seismogram and with the help of the path-time curves by noting the time of onset of the different kinds of waves and by observing the direction of the incoming waves. The agreement of the results of both methods is shown, for instance, by Gutenberg (600) for the above-named quake of November 16, 1911. Further references should be made to the work of Galitzin (506), Zeissig (1659, 1660), Klotz (813), Rudolph and Szirtes (1320), Rosenthal (1303), Mohorovicic (1128), Inglada (770*a*), and others. Sieberg (1443, p. 517) has collected some simple approximate formulae for the determination of the epicentral distance.

Through the comprehensive working-up of data from about 25,000 earthquakes, Sieberg (1442) could show that a clear connection exists between the tectonic basal elements of the crust of the earth and the distribution of the earthquake centers. Table XIX shows these relations for perceptible earthquakes in percentages of the total annual number.

TABLE XIX

Tectonic basal element	Perceptible earthquakes	
	All degrees of intensity	Severe
Old land masses and tables	1.4	2.4
Paleozoic core formations	0.4	0.3
Faulted basins	2.7	6.7
Fractured regions	21.6	26.4
Normal Tertiary folded formations	3.6	5.8
Erroded Tertiary folded formations	23.7	36.9
Land regions in deep-sea grabens	40.6	21.5

In addition to the above-mentioned work (1442), a comprehensive survey of the connection of the spatial distribution of

earthquake centers with the great tectonic lines in the structure of the crust of the earth is given by Sieberg, with detailed references to the older literature, in his Erdbebenkunde (1443, pp. 373–425). Further reference should be made also to the comprehensive investigations of seismic geography by von Hoff (730), Montessus de Ballore (1133), Frech (485), Rudolph (1319), Rudolph and Szirtes (1321), and others. On the seismicity of individual limited land regions, numerous works have been submitted, of which only a small selection can be named. Scheltle (1355) discusses the earthquakes of Germany in relation to its tectonics. Lais and Sieberg (893) treat of the relation of the seismic activity of south Germany to its geologic structure, especially in the instance of the discussion of the quake of November 16, 1911, Lais (891) particularly the seismicity of the Kaiserstuhl region near Freiburg i. Br. In a typical exposition, Regelmann (1279) discusses the earthquake centers and focus lines in southwest Germany and their relation to the tectonic organization of this region. The seismic ground movements felt in east Prussia are traced by Errulat (426) to groundwater movements and settling phenomena in those places. Tams (1508) worked up the seismic relations of the European North Sea, Pautsch (1215) those of the Mediterranean Sea. Sieberg (1443*a*) observes in the earthquake period of December, 1924, to January, 1925, in southern Central Europe, an example of the wandering of the epicentrum along the boundaries of the Adriatic depression field. Heritsch (712) analyzes the earthquakes in the northeastern Alps and places them in relation to the fracture lines there. Inglada (765*b*) describes the seismic geology of Spain. Baratta (99), in 1901, gave an example for the seismic description of a country in his "Italian Earthquakes." Individual features of the connection of earthquakes in France with the tectonic organization of that country are discussed by Noguès (1184) and Lemoine (939). Some data for Belgium are given by Simoens (1447*b*). The seismic history of Great Britain is set forth by Davison (334*a*). The earthquake activity and the tectonics of Spitzbergen have been systematically collected by Sieberg (1440). A comprehensive exposition of the tectonics, the vulcanism, the earthquakes, and the gravity anomalies in the fault zone of East Africa is due to Krenkel (872). The relations between the main earthquake centers and the morphological connections in North America are treated by Deckert

(338). The California earthquake is discussed by Tams (1513) from a similar point of view; for South America the "Seismic History of the Meridional Andes" is presented by Montessus de Ballore (1135). Navarro-Neumann (1156) collected the seismic relations of Spain in especially clear form.

In most earthquakes, the focus lies so deep that in the focal line along which the earthquakes are often formed only the basic lines of tectonics come to expression. Therefore the question of the focal depth also possesses essential interest here. The elastic disturbances on the earthquake focus in general seem to have only a slight spatial extent, since otherwise it would be impossible to explain the sharp seismogram with clearly recognized disturbance onset. In other cases, however, the shocks also emanate from a longer section of a line of tectonic disturbance.

The determination of the focal depth on the basis of the seismogram is an especially difficult problem of seismic investigation. Kövesligethy (864), Inglada (768), and Oldham (1196*b*) sought to derive the focal depth from the manner of decrease of the quake intensity from the epicentrum. The determination of the focal depth from the characteristics of the time-distance curve appears more reliable, according to de Quervain (1259), Mohorovicic (1127), Geiger (523), Gutenberg (601), Inglada (770*a*), and Kreis (871). Kunar Banerji (94) sought to determine the focal depth from the amplitude relations of the space and surface waves. The different methods of calculation of the critical focal depth are examined by Rosenthal (1302); comprehensive discussions are offered by Gutenberg (1443, pp. 344 and 145, as well as 613*d*, p. 271 *et seq.*) and Mainka (1258, p. 221 *et seq.*). The focal depths calculated according to the different methods, however, vary within wide limits, especially because of the inaccuracy of the time correction of the seismograph stations. The introduction of wireless time signals may reduce these inaccuracies. In order to make more accurate calculations possible, (according to Gutenberg 601) the initial onset time must be obtained correctly to within several tenths of a second at numerous observation stations in the vicinity of the focus. Thus, for example, the focal depth of the central European earthquake of November 16, 1911, of which we possess the most comprehensive and reliable observed data, varies according to different methods between 133 to 164 km., according to Schmidt

(1393), and 9.5 km., according to Galitzin (510). The inspection of all present data, however, shows that earthquake foci may be found only between 0 to about 60 km. depth, and chiefly at 20 to 30 km. (see Mohorovicic (1129)).

The Influence of the Geologic Structure of the Uppermost Formations of the Earth on the Propagation of Earthquake Waves. For the study of the geologic structure of the uppermost earth formations, the feeble quakes which occur near the surface possess an especial interest. Mohorovicic (1123) found in the Kulpatal quake a velocity V of 5.6 km. per sec. for the longitudinal waves, and v of 3.2 to 3.3 km. per sec., while de Quervain (1260) in the three tunnel quakes of Grenchen calculated $V = 5.1$ to 5.25 km. per sec. and $v = 3.0$ to 3.1 km. per sec. De Quervain (1262*a*) found by observing an afterthrust of the earthquake at Visp (Switzerland) on a seismograph brought there after the main quake, and simultaneous registration in Zurich, a velocity $V = 5.57$ km. per sec. A treatment of these same observations with reference to local geological conditions, however, does not seem to have been made yet.

In order to utilize quakes with deeper focal positions at greater epicentral distances for special geologic investigations, one must take as a basis the variations of the observations actually found at a station from the interpolated normal values of the observations of a greater net of stations for the station in question corresponding to their geographic position. Such a method is obviously possible only in the case of very exact and comprehensive observed data with excellent time determinations. The requirements are highest for the evaluation of the longitudinal and transverse waves, since these waves with increasing epicentral distance arrive ever more nearly perpendicular to the surface and therefore travel ever shorter paths in the uppermost earth formations to be investigated. In the evaluation of the observations on the surface waves which proceed continually in the uppermost zones of the earth, the relations are perhaps more favorable.

Up to the present, investigations on the propagation of the long waves refer almost exclusively to the average values over large regions which have been traversed by the surface waves, and concern themselves with the average speed of propagation and the absorption of these waves, and with the dependence of these quantities upon the wave period. Also, the most promi-

nent wave periods and amplitudes of the main vibrations have been statistically studied with reference to dependence upon the geographic position of the epicentral region, the condition of that portion of the earth, traversed and the geologic character of the subsoil at the place of observation.

The theory of the surface waves under consideration, *i.e.* the changes of the elastic constants in the uppermost earth formations, is treated, for example, by Love (981; 982, Art. 176), Matzusawa (1056*a*), Jeffreys (762*e*), and Meissner (1072). The average speed of propagation of the surface waves, according to Tams (1509), Angenheister (44), Gutenberg (606, 613, 613*b*, 613*c*), and Hodgson (727*a*), is greater under the Pacific Ocean than on the continental masses. Angenheister (44) found for oceanic space an increase of about 21 to 28 per cent in the velocity of the surface waves. (Also the longitudinal waves, according to Angenheister (44), have a higher velocity under the ocean at 50 km. depth than under the continents.) Rudolph and Szirtes (1322), Rosenthal (1301), Pechau (1216), and others have investigated the dependence of the velocity of the long waves upon the geographic position of the epicentral region for different European countries. Of especial importance for practical investigation are the surface waves on the bounding surfaces between formations having different elastic properties, on whose special structure, however, only very little is known. Theoretically they have been entirely neglected; only Jeffreys (762*f*) has concerned himself with this problem, and he found surface waves (two-dimensional waves) with a velocity of propagation which is equal to the velocity of the longitudinal waves in the elastically harder medium. Increased attention should be given to these waves, since the decrease of the energy density in the direction of propagation may be far smaller with the surface waves than with space waves.

With explosions, one almost always obtains surface waves with velocities down to 100 m. per second, whose nature is still unknown. Gravity may play some part in their formation. Angenheister (51, p. 32) also reports on the appearance of very small velocities of propagation with explosions. In blasts in loose soil, these slow waves contain almost the entire energy received from the soil. The harder the soil is, the smaller will be the amount of energy transmitted in the form of such slow wave trains.

It is astonishing that, according to Pechau (1216) and Mack (1020), the velocity of the surface waves which come immediately from the focus, is somewhat greater than those surface waves which have circled the earth and for which the average value seems to be about 3.3 to 3.4 km. per second. From a number of investigations, for instance by Rudzki (1323), Kövesligethy (865), Wiechert (1610), Angenheister (40, 41), Wegener (1593), Meissner (1074, 1077), Galitzin (514), Gutenberg (604), there appears a dispersion, since with the surface waves the shorter shows a somewhat lower speed of propagation, and is proportionately more strongly absorbed. Wegener (1593) refers to the fact that the absorption varies considerably with different quakes, which may be connected with the amplitude and period relations (always individually developed) as determined by the character of the processes at the focus at the time of origin of the quake. Gutenberg (613*b*, Table XX) is reluctant to agree to this, but contends that the paths which the waves travel determine the absorption relations. Angenheister's remark (44) is important for us, that the absorption under the oceans is greater than within the continents; this Gutenberg (604) confirms. Service (1431*a*) explains the greater wave velocity under the oceans as a result of the greater density of the ocean floor, which is in accord with our formulae for V and v on page 205. Gutenberg (606) derives from the periods and the dispersion of the surface waves approximate values for the thickness of the surface formation (Sima) in the different geographic divisions, which he values in Eurasia at 55 km., in America at 50 km., in the Atlantic and the Arctic at 25 km. thickness, while in the Pacific such a formation is lacking or possesses some thickness less than 10 km. As a result of the partial energy reflection at the vertical bounding surface of the continental shore lines, the seismic waves which cross the Pacific boundary are considerably attenuated (*cf.* Gutenberg (605)). Gutenberg (613*c*, 613*d*, p. 268 *et seq.*) refers to the fact that short waves which are generated by the advancing wave front in the interior of the earth, probably have a higher velocity than the original waves (dispersion). The velocity of propagation of energy (train velocity) can eventually be raised as much as 20 per cent over the normal velocity.

Reich (1287) investigated the influence of the position of faults, folded mountains, etc., on the speed of advance and amplitude of the surface waves, and established that such

tectonic formations along the direction of propagation of the wave transmit the waves with maintained intensity, while those perpendicular thereto have a pronounced attenuating effect. Corresponding observations have also been made by Haussmann (645) in the Aachen region and by Monti (1136) in the Swiss Alps (see also Conrad (316*a*)). The influence of the great fracture zones in the crust of the earth on the propagation of earthquake waves is shown by Gherzi (546) with the help of records of the seismic stations in Zi-ka-wei, Cartuja, La Paz, and Sydney (see also Somville (1465*a*)). Gutenberg (606, 613*c*) treats of the connection between dispersion and extinction of seismic surface waves and the structure of the uppermost earth formations. The intensity relations of the different kinds of waves to each other, according to Zoeppritz, Geiger, and Gutenberg (1668) is dependent upon the character of the processes at the earthquake focus.

The periods of the earthquake waves as affected by the place of origin of the quake, by the path traversed, and by the position of the receiving station, have been studied by Omori (1198), Rösener (1300), Meissner (1076), Angenheister (44), and Wellmann (1597) among others. Almost always, periods of 12 and 18 sec. were found, occasionally of 16 sec. A dependence of the fundamental periods upon the direction from which the waves come and upon their course under oceanic or continental formations can almost always be established (see also 613*b*, p. 77). Meissner (1076) also observed in Potsdam much greater period lengths of 23 to 60 sec. Gutenberg (599*a*) often finds in the longitudinal earthquake forerunners in the vicinity of the focus small irregular periods which he ascribes to vibrations of thin formations.

A systematic investigation of the dependence of the periods of the surface waves upon the geologic conditions at the focus and at the receiving stations (station vibrations) might perhaps be desirable. The well-planned investigation of the position and boundary of masses in which are excited free vibrations by the transient seismic waves may give rise to important geologic information. Whether the periods of 12 and 18 sec., as noted, always appearing at many stations can be connected with resonance vibrations (perhaps also as harmonics) in the 60 km.-layer which forms the earth's crust, has been discussed by Rösener (1300), Angenheister (44), Geussenhainer (541), and Gutenberg

(1443, p. 360 *et seq.*); but the explanations are not conclusive. The conditions for the observed appearances and development of vibrations perpendicular to the direction of propagation of the surface waves have been explained by Wiechert (1612), Love (982), Meissner (1072), Jeans (762*aa*), and Angenheister (44). By making a study of these vertical vibrations, one can derive, especially in consideration of the great variability in their appearance, many important conclusions concerning the structure and the thickness of the uppermost crustal formations.

The Seismic Ground Unrest.—A special group of surface vibrations is formed by the ground unrest whose causes and conditions of occurrence have been discussed by Gutenberg (609 and 613*d*, p. 302 *et seq.*) in a series of monographs. We can therefore limit ourselves to a very brief discussion, so far as the ground unrest either can be employed as a source for the recognition of the character of the uppermost earth formations, or comes into consideration as disturbances in the surveying of ground movements emanating from artificial earth tremors.

As seismic ground unrest one includes the continual ground tremors of all periods, called forth by other causes than earthquakes, which are noticeable on the seismograph, and in rare cases directly for man's perception. They have already been observed by Milne (1107, 1112), Rebeur-Paschwitz (1276), and others. Hecker (661) divides these movements according to their average period of duration T_m into four classes, as follows: 1. $T_m < 4$ sec.; 2. $T_m \sim 7$ sec.; 3. $T_m \sim 30$ sec.; 4. $T_m > 1$ min. Of these, the movements of Classes 2 to 4 extend over large regions at the same time, while Class 1 arises from local causes. A similar division has been made by Galitzin (497). Gutenberg (597) first differentiated the movements into two classes; movements due to local, and those due to distant, causes. Later (609, p. 4) he subdivided this grouping further and differentiated between:

1. Movements due to industry and traffic.
2. Local movements due to waterfalls and similar tremors.
3. Movements due to volcanic processes.
4. Movements due to direct effects of local storms and squalls on high objects, as well as movements resulting from quick changes of air pressure.
5. Long periodic movements due to friction of the air on the soil.

6. Local movements due to breakers (surf).
7. Trembling of whole continents due to steep coastal surf.
8. Movements by frost.

Ground unrest of the shortest periods is brought about by industry and traffic. This kind of ground unrest, because of the short periods, is often especially disturbing for seismic investigations. Directional observations on such feeble vibrations were made by Grunmach (586) in 1886. The ground unrest excited by a large gas machine was investigated by Mintrop (1116), the observed period corresponding to the number of revolutions of the machine. He could detect the ground vibrations produced by a gas engine at 400 m. depth; on the contrary, the ground unrest from traffic which was observed at the surface of the earth at Potsdam, according to Schweydar (1423) was no longer noticeable at 25 m. depth. According to Benndorf (1400), two seismographs, one of which was located at 1,100 m. in the mine of Přibram in Bohemia, the other at the surface of the earth, showed the same magnitude of ground unrest. Hecker (668) established that the entire mountain mass if moved could give rise to the observed ground unrest. According to Gutenberg (597), the ground unrest due to surf was essentially smaller at 700 m. depth in a mine at Clausthal than at the surface of the ground at Göttingen; however, the completely different geologic character of the subsoil in the two places must be taken into consideration, and precludes direct comparison. According to Nakamura (1151*a*) and others, earthquakes are less noticeable in the interior of tunnels than at the outlets.

Natural vibrations of rock masses with periods of 0.029 and 0.005 second were detected by Grunmach (587, 588) at the Queistalsperre, as a result of the falling water. Whether the anomalies of ground unrest in Jena and Potsdam, which Gutenberg (599) established, were brought about by individual vibrations of masses in the vicinity of the station (station vibrations) is still not clear. There is a reference by Laska (919) on the possibility of explaining the ground unrest in eastern Europe as due to free vibrations of the Russian plateau.

The ground unrest resulting from volcanic processes is confined to the vicinity of active volcanoes. According to Omori (1201), definite periods (perhaps harmonics of a general fundamental vibration) seem to appear.

The ground unrest originating from locally strong air currents or storms is very widely distributed. It can severely affect the observation of other processes in practical geologic measurements in the field, especially if an immediate effect is possible of the air movement on the apparatus or a tent in which it is placed. The apparatus for this purpose must therefore be always so constructed that all parts sensitive to vibrations can be connected rigidly to the ground, while the registration apparatus must be insensitive to vibrations. Up to the present, these factors have not been considered in the use of most existing vibration recorders (see Ambronn (33*k*)).

The periods of tremors produced by local storms and the like, according to Omori (1199), Gutenberg (597), Errulat (425), and others, lies between 1 and 10 sec., principally between 4 and 7 sec. Local changes of air pressure, according to Lewitzki (946) and Galitzin (514), produce a similar effect. Hecker (661), Galitzin (500), Meissner (1075), Gutenberg (597, 609), and others attributed to friction of the wind on the soil, earth movements having periods of 10 to 60 sec. and often having appreciable amplitudes, especially in summer (in Potsdam for instance up to 50μ).

One of the most important factors in the generation of ground unrest is the surf on steep coasts. After Wiechert (1609) had made noteworthy reports on these causes, his student Gutenberg (596, 597, 599, 607, 608) extended this hypothesis in numerous researches, so that today one may look upon the surf on steep coasts as the principal cause of the normal ground tremors with period lengths of 4 to 10 sec. observed in various parts of Eurasia and North America. Besides this, other causes, as air-pressure changes, wind, and wave pressure on the sea bottom can come into consideration, according to Mazelle (1067), Günther (593), Meissner (1075), Biot (187), Gherzi (545), Kanar Banerji (94*a*), and others.

Also the annual and daily periods of the seismic ground tremors in Europe and Asia as far as Irkutsk are related in time of occurrence to the motion of the breakers on the steep coasts of Norway, Scotland, and France. Gutenberg (597) has also been able to prove this connection numerically according to the theory of correlations. Linke (959) found similar relations for Asia after a very thorough investigation.

The periods of vibration of the seismic ground tremors due to surf increase in general (according to Gutenberg (599), (609)) with the distance from the point of origin; Linke (959) sought to use this principle for the determination of the paths of storms and thereby for weather prophecy. According to Linke (959) and Mainka (1032), they also show an annual fluctuation; in summer, the periods are predominantly under 5 sec.; in winter they are predominantly over 5 sec. According to Schneider (1400) for Vienna, Galitzin (497) for Pulkovo, Gutenberg (597) for Appia, Clausthal, Göttingen, Hamburg, Leipzig, Potsdam, Pulkovo, and Vienna, and according to thorough investigations of Hecker (667), in most places of observation the period increases with amplitude.

Important conclusions may be drawn from the spatial distribution of the average amplitude of the ground unrest in Europe and Asia, for which Gutenberg (596; 609, p. 22 *et seq.*) has arranged the relative values of a great number of stations. Gutenberg (609, p. 43) also shows how these relative values are characteristically influenced according to the region of momentarily strongest breakers in northwest Europe. On a small scale map, Gutenberg (599; 609, p. 54) and Sieberg (1443, p. 355) show the influence of European tectonics on the propagation of the ground unrest resulting from surf on the different coasts. The effect of the most important tectonic elements is thus very clearly shown.

The influence of the subsurface formations of the observation station itself on the magnitude of the normal ground unrest has been variously observed. Omori (1200) shows that among Japanese stations those on Quaternary formations showed greater unrest than those on granite. Klotz (812), Rudolph (1318), Schuster (1412), and Hecker (663, 667) emphasize the effect of the geological and tectonic condition of the station subsoil on the intensity of the ground unrest. Gutenberg (599, 609) gives a grouping of his relative values of the ground unrest in relation to the geologic condition of the subsoil. These have been collected in the first column of numbers of Table XX. The relative numbers, however, do not consider the geographic position. There have been given, therefore, in the column, values which consider the position of the station from points on the Spanish, French, English, and Norwegian coasts (the last with doubled intensity corresponding to its greater longitudinal

extent). In order to make calculations of the extinction, etc., in a simple manner, a decrease of the effect with the square of the distance is assumed as the first approximation.

TABLE XX

				Average
Sand and loam on rock...	Königsberg	7	13.0	13
Rubble.....	Strassburg	8	10.6	8.8
	Munich	4½	8.8	
	Laibach	4	8.2	
Loam, loess.....	Belgrade	(1½)	(6.2)	8.0
	Pulkovo	2½	5.8	
	Vienna	4½	9.2	
Tillite.....	Hamburg	8½	10.7	7.2
	Breslau[1]	(1½)	(3.4)	
Alluvium.....	De Bilt	8	7.9	7.2
	Budapest	2	6.6	
Clay (By Sieberg rubble).	Graz	2.	5.5	5.5
Sandstone.....	Jena	2¾	4.6	4.2
	Aachen	3½	3.7	
	Heidelberg	3½	4.9	
	Triest	1½	4.0	
	Zurich[2]	½	(0.8)	
Basalt.....	Clermont	5	4.2	4.2
Limestone.....	Göttingen	2¾	4.0	4.1
	Uccle	3½	3.1	
	Paris	7	4.1	
	Cartuja	3¾	4.9	
	Besançon	3	3.4	
	Marseille	4	(6.1)	
	Nördlingen	2	3.3	
Sand.....	Potsdam	2½	4.1	4.1
Silurian.....	Eskdalemuir	6½	2.7	2.7
Quartzite rock.....	Feldberg (Taunus)	(2)	(2.7)	(2.7)
Primitive rock.....	Upsala	1½	1.2	1.2

[1] Has perhaps twice as great a value.
[2] Probably very closely cemented rock.
(Both from a kind private communication of B. Gutenberg.)

In certain cases, by comparison with the records at stations with known subsurface coefficients, the ground unrest can also serve as a clue to the character of an unknown subsoil.

Hecker (667, 669) in Strassburg, and Shaw (1435) in West Bromwich sought to determine the speed of propagation of the waves of the ground unrest. The results are somewhat indefinite, since the direction of the propagation was not known and the identification of the disturbances on the two seismographs

situated at 0.02 to 16 km. distance from each other was not more exact in details. Since the ground unrest may in general be composed of several individual movements with different directions of advance crossing one another, it seems questionable whether the proposal of Mainka (1036, p. 137) to establish the directions of advance, without assumptions, by means of three seismographs placed at the corners of an equilateral triangle, will be successful. The beautifully developed wave trains of about 2-min. duration interspersed with the waves of the normal ground unrest, often noticed, and which have been investigated by, among others, Schneider (1400), Gutenberg (597), Geussenhainer (541), may also be explained as interference phenomena between crossing wave trains. Dale (327) investigated the composition of such individual vibrations which occurred among the normal waves of ground unrest.

The long period waves of ground unrest with very great amplitudes up to ½ mm., which, according to Gutenberg (597), are produced by frost, have been little investigated up to the present. The long periods of these waves (up to 8 min.) may also preclude any practical application for geophysical exploration purposes.

Seismic Apparatus.—After the most important characteristics of the origin and propagation of natural earthquake waves in the earth's subsurface have been discussed, further discussions may concern themselves with the instrumental contrivances which have been devised for recognizing, measuring, and analyzing the vibration processes in the earth's crust.

The contrivances used for this are designated as seismoscope, seismograph, tremor meter, vibrograph, accellerograph, etc., according to their properties and particular purposes of application.

To go into the general basis of the theory of the seismograph would lead us much too far; therefore let reference be made for this to the basic expositions of Wiechert (1607), Galitzin (514), Kövesligethy (863), and the notes of Schlüter (1371), Rudzki (1325), Mainka (1258, p. 191 *et seq.*) (1036), Sieberg and Gutenberg (1443 and 613*d*, p. 221 *et seq.* and p. 589 *et seq.*), and to the critical remarks of Mohorovicic (1125). Although the method of operation of most of these instruments depends on the same theory of forced elastic vibrations, for our purposes they will be separated into three groups on practical grounds.

We shall differentiate (see also Ambronn (33*f*)):

1. Contrivances which are designed to show directly the displacement of the ground itself;

2. Contrivances which indicate the instantaneous velocity of the ground movement;

3. Contrivances which measure the acceleration in the movement of the subsoil.

In each group one will have to distinguish for the time being the mostly stationary and heavy instruments (seismographs) appointed for the solution of the purely scientific problems of earthquake study, from the light portable contrivances (tremor meters) built for the practical working out of geologic problems in the field or for the solution of technical questions.

Apparatus for the Determination of the Ground Disturbances Themselves.—As a general basic type of the contrivances of the first group, one may consider a mass which is so arranged that each momentary displacement from its position of rest in any direction is opposed by a force proportional to its displacement. As a model of such an arrangement, one may consider (with small displacements) a mass M (Fig. 73) which hangs freely by means of a spring F rigidly connected with the earth at the point A. The strength of the spring F is so measured that the force with which it moves the mass M to its position of rest after small displacement above or below, is equal to the force with which gravity will bring back to its position of rest the mass (as a pendulum) after an equal horizontal displacement. If the mass M is displaced from its position of rest and then released, it describes free oscillations about its position of rest with the period of vibration T.

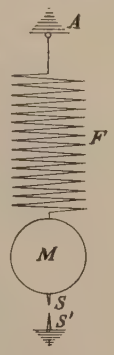


FIG. 73.

If the suspension point A of the contrivance experiences a very quick displacement q towards T, then for the first moment M remains at rest because of its inertia; the point s, fastened to M, is shifted relative to the mark s' fastened in the soil also an amount q, but in the opposite direction. At once, however, the elastic force of the mass M seeks to return it to its position of rest at A, where it eventually comes to rest. A small displacement of the mass M in the direction of its new equilibrium position always occurs during this movement. The displacement

between s and s' no longer attains the full value q, but is increasingly smaller the slower the displacement proceeds.

If the ground on which the apparatus is placed experiences, not a single, but periodic, displacements back and forth, whose course with reference to time may be expressed by a sine function, then the mass M with the pointer s describes forced vibrations relative to the mark s', which may also be expressed by a sine function. If the period of the displacement of the ground (the so-called disturbance period) is T' and its magnitude in a definite direction is equal to q, then the displacement (the greatest throw) of the marks s and s' relative to each other is

$$q = \frac{T^2}{T^2 - T'^2}.$$

The amplitude of the movement of the mark s will be dependent upon the relation of the disturbance period T' to its own period T. The movement of the mark shows the true movement of the ground enlarged or reduced. If T' is very small compared to T, then the displacement of the marks relative to each other is equal to the ground displacement q. If T' is equal to T the magnification is infinite, as resonance occurs. If T' is large with respect to T, then $T^2 - T'^2 = -\infty$, and thus the magnification equals zero. In general, s remains opposite S' as if at rest.

Because of the great dependence of the magnification upon the disturbance period T', such a free pendulum is practically of little use. Therefore one adds a damping device to the pendulum, which constantly absorbs vibration energy in proportion to its momentary magnitude of movement (mass $\times$ velocity). When thus provided with damping, a pendulum once struck describes vibrations whose amplitudes decrease according to an exponential law. The ratio of two successive swings (thus on different sides of the position of rest) is called the damping coefficient. With seismic pendulums, in which the damping was introduced by Wiechert (1607) in 1899, damping coefficients of about 5:1 and higher are usually chosen. If one increases the damping so much that the pendulum can no longer swing past the position of rest, then the pendulum is aperiodic.

By the damping, the period of the pendulum, *i.e.*, the time intervening between its successive passages in the same direction through the position of rest is increased; the magnification is diminished especially in the region of the resonance; furthermore

a phase retardation enters between the ground movement and the pendulum movement as compared to the vibrations of a free pendulum. Relative to the details, reference must be made to the above-named exhaustive expositions. The advantage of the damped seismograph is shown most clearly by Hecker (660). The damping device can be secured in very different ways. Thus, for instance, Wiechert (1607, 1608, 1611, 1615) and Hecker (1443, p. 445) use air damping, Mainka (1258, p. 201 *et seq.*) fluid damping, Galitzin (496, 503, 514, p. 262 *et seq.*) electromagnetic damping.

In many seismographs, the amplitude is also reduced by the friction of the individual parts on one another. The force of the friction is always opposed to the direction of motion; consequently the amplitude of the vibrations with friction alone always decreases in constant ratio from period to period (see also Reid (1291*a*), Mohorovicic (1125*a*)).

Now if we consider the distance between s and s' not immediately, but through a microscope with the magnification V, then V is called the magnification factor. The magnification factor thus also gives the magnification of the true movement of the ground. With a natural period T and a disturbance period T', the true magnification (without damping and friction) is:

$$V = \frac{T^2}{T^2 - T'^2}.$$

In practice, instead of the microscope a lever system is used which magnifies the movement of s with respect to s'. The movement is at once resolved into two horizontal components perpendicular to one another, and a vertical component. This leads to a type of construction which corresponds somewhat to the Quervain-Piccard universal seismometer (1235, 1262, 1263); Maurin and Eblé (1059) also describe a similar seismograph.

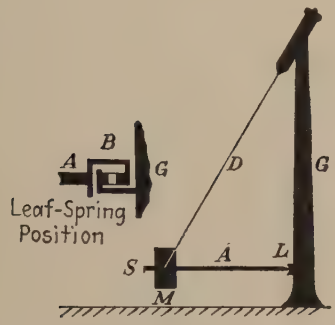
In general, it is customary in practice, however, not to arrange the mass M freely movable in all directions, but to allow it one, or at most two, directions of freedom, since (as Mainka (1033; 1036, pp. 129 and 142; 1258) has advocated strenuously in discussing the construction of seismographs) the danger of reciprocal action between lever systems is to be feared when the coupling of the magnification lever system is arranged to show two or more components of the movement, the danger of reciprocal action between the lever systems is to be feared. Wiechert,

however, in his horizontal seismograph, today the most widely used of all types of seismographs, has retained the coupling of the lever system for both horizontal components to one mass.

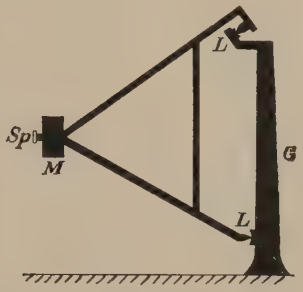
In the selection of a seismograph or tremor meter the amplitude of the tremor to be surveyed determines the amount of magnification to be used, and the range of the disturbance periods especially to be investigated determines the choice of instrument period. Corresponding to a subdivision, recognized as expedient by Wiechert, of earthquakes into local (near) earthquakes and distant earthquakes of average to great epicentral distance, one uses seismographs with $T \leqq 2$ sec. at $V = 1{,}000$ to 2,000, with $T = 6$ to 20 sec. at $V = 200$ to 300, and finally with $T = 50$ to 60 sec. at $V = 10$ to 20; the last in order to be able to study the long surface waves which emanate from world quakes. For technical tremor measurements with artificial earthquakes, very much shorter disturbance periods often come into consideration, for which special tremor meters have been constructed.

In order to attain the necessary free period (without damping) for the above-named purpose, simple pendulums are not used, as they become much too long. Many ways have been found to circumvent this difficulty. A collection of the most important older types of seismometers are described by Ehlert (381). Figure 74*a-e* shows some types in schematic representation after Sieberg (1443, p. 436; see also Gutenberg 613*d*, p. 220 *et seq.*). Figure 74*a* illustrates the type of conical pendulum with pointed bearing, as it has been used by Vicentini, Omori, Bosch, Milne, Agamemnone, Galitzin (502), and others. The lower bearing L was replaced by Mainka (1030), in accordance with a proposal of Ewing, with a flat spring; *b* shows an earlier form of the horizontal pendulum which was used on the seismographs of Rebeur-Paschwitz (Hecker (657)); *c* is a bifilar pendulum described by Hengler (700) and Zöllner (1665) and used by Galitzin (495; 514, p. 249); the inverted vertical pendulum as shown in *d* illustrates the basic form of the widely used Wiechert horizontal pendulum (1607, 1608). This pendulum is astatic. It is in unstable equilibrium on its under bearing L (consisting of leaf springs). The elastic restoring force is produced by flat springs.

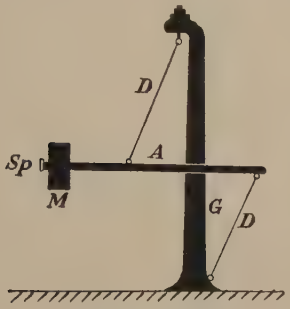
The natural period of this instrument, *i.e.*, the duration T of a complete oscillation of the mass M about its position of rest,



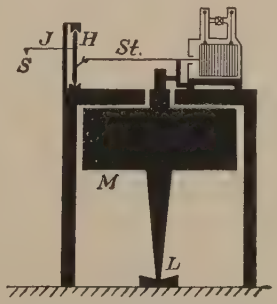
(*a*) Conical pendulum with point.



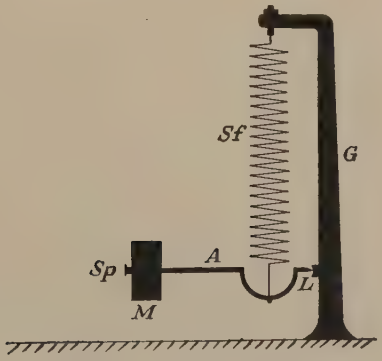
(*b*) Two-pointed horizontal pendulum.



(*c*) Bifilar pendulum.



(*d*) Inverted vertical pendulum-air damping.



(*e*) Astatic vertical seismograph.

FIG. 74.

after removing all damping, is equal to the equivalent pendulum length L according to the equation

$$L = g \frac{T^2}{4\pi^2} \ (g = \text{acceleration of gravity}).$$

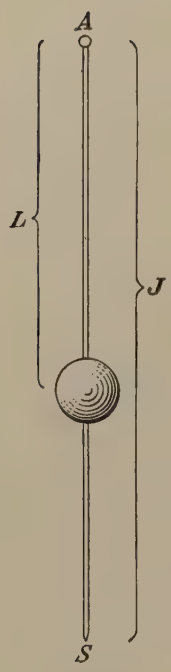


Fig. 75.

The "indicator length" J corresponds to the indicator sensitivity and gives (Fig. 75) the distance from the suspension point A at which one must put the mark s on a simple pendulum of the equivalent pendulum length L in order to obtain with the simple pendulum the same indicator sensitivity, *i.e.*, sensitivity at momentary displacement, as with the seismograph in consideration. The relation $V = J/L$ is thus the indicator magnification.

The present models of vertical seismographs also hold good with respect to the periodic relations. A simple spring (spiral or plate spring), attached directly to the mass itself, has been used as the restoring force (for instance by Vicentini). The tremor meter employed by Mintrop (1119) had a simple plate spring. A notable increase in the period of the pendulum is obtained by the arrangement shown in Fig. 74*e*, where the mass M is fastened to an arm A, to which the spring F is attached at a point between the rigid mass and the torsion point. A further increase in the period (up to astasia) is obtained, if the supporting spring is attached under the lever arm in the manner shown. The vertical seismographs of Wiechert (1607, 1611) and Galitzin (514) are built according to this principle.

Ideas which Mainka (1030; 1258, p. 206) entertained about the use of different seismograph constructions for different displacement components, especially in the derivation of the true ground movement (for instance in directional determinations), can be satisfied by spring elasticity only if the three components perpendicular to one another all show the same angle toward the horizontal plane (see also Galitzin (512)). A rotational seismometer was recently described by Mainka (1030), and a torsion seismometer by Anderson and Wood (37; see also 613*d*, p. 223).

Schmaltz (1372) proposes to register, by means of a string galvanometer, changes of electromotive force caused by the tremors in a capillary electrometer (1148, p. 585 *et seq.*). Duckert (362*b*) devised a seismometer in which the movement of an elastically suspended plate of a condensator relative to a rigid one, is observed by means of capacity measurements with application of high-frequency electric currents.

For the investigation of artificial quakes, the propagation of explosion waves, machine vibrations, etc., in the registration of the movements themselves, the same basic constructions come into application as in the contrivances designed for the study of natural earthquakes (see, for instance, Duffing (365), Hort (742)). The periods of such vibrations are in general very much shorter, and require manifold precautions in order to prevent disturbing influence due to the natural periods of the receiving apparatus. Especially to be considered are the natural vibration periods and harmonics of individual parts of the apparatus, which are not observed in the investigation of the relatively long-period natural seismic waves. These vibrations are often almost entirely undamped, and thus in the case of resonance can assume very great amplitudes, and distort the results entirely. The most careful investigations are always necessary in this direction. Mainka (1035) reports on this incidentally in a comprehensive paper on the different types of tremor meters.

As an example of a tremor meter which is constructed on the principle of Group I, and which is still used for earth investigations, that of Mintrop (1119), Fig. 76, after Heiland, may be described. This is clearly very similar to the apparatus built by Schweydar (1425*b*) in 1915. The mass 1 is fastened, (for instance, see Vicentini), to a leaf spring. On the mass is erected a cone 4 of thin aluminum plate as the first lever arm to amplify the movement. This cone carries a friction surface which rubs on a thin round rod which is rotated between pointed ends. The friction of the contact surface is increased by magnetization according to the models of Fontaine (467) and others. On this rod is fastened a mirror which rotates with the rod. A beam of light falling on the mirror is reflected at twice the angle of this rotation, intercepted on a photographic paper and recorded in its movement. Unfortunately, up to the present neither determinations of the instrumental constants nor test curves of this contrivance are known, so that it cannot be

estimated as to what extent disturbing singular vibrations of different parts, and zero-point changes through slipping on the frictional surface, will occur with this part mechanical, part optical, magnification, nor how accurately a quantitative analysis of the ground vibrations can be made. Registrations with this instrument published by Gutenberg (613*d*, p. 604) and Hort (742) show that very great quantitives of explosives are necessary

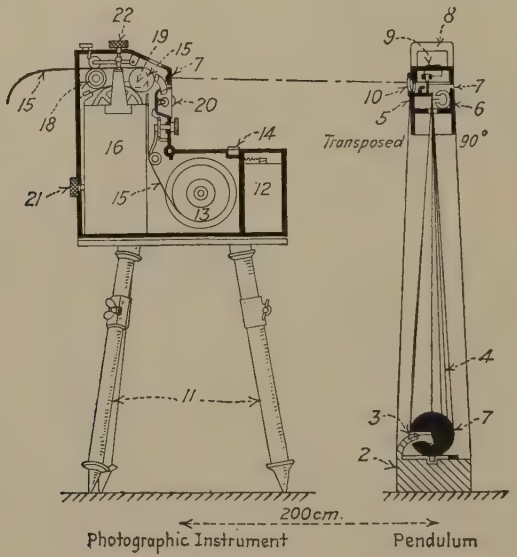


FIG. 76.—1. Lead sphere (about 10 kg.) as mass. 2. Supporting plate. 3. Plate spring as elasticity. 4. Aluminum helm. 5. Adjustment magnet. 6. Damping magnet. 7. Mirror axis and mirror. 8. Handle. 9. Level. 10. Converging lens. 11. Stand for photographic instrument. 12. Element for incandescent lamp. 13. Film roll. 14. Level. 15. Film strip. 16. Clockwork for driving the film recorder. 17. Cylindrical lens. 18. Driving roll. 19. Time pendulum. 20. Lamp. 21. Arrester. 22. Knob for paper revolver and time pendulum.

in order to obtain recognizable onsets, and that the damping is very slight. On account of the back swings of later vibrations, onsets blend with one another, and pronounced resonance effects are apparent. When this happens, the registration of the ground tremors can no longer be resolved. The seismograms obtained with a very similar apparatus and published by Schweydar and Reich (1425*b*) exhibit the same properties. Rothé and others (1307*a*) give instrumental constants of a Minthrop apparatus, and emphasize the disadvantage of its insufficient damping.

The apparatus of Norton (1187) (see also Weyl (1603*a*)), which has been designated as an acceleration meter, is also to be considered in Group I because it has combined mechanical and optical enlargement. The apparatus is designed for high-frequency disturbances. Its dimensions are kept as small as possible in order to make disturbing instrumental vibrations impossible.

A few words may be devoted to the question of registration. Subjective observation does not come into question. By far the most-used methods are the registration by fine glass or metal points on slightly sooted glazed paper and the photographic registration method on paper sensitive to light. Because of the friction in the amplifying mechanism and on the paper, the carbon recorder requires a very-large-size seismograph. Fleiss (455) and Mainka (1030) have reported on investigations on friction, etc., in carbon registration. Galitzin (509) makes theoretical observations on this question. The initial cost of a carbon recorder is high, but the operation is cheap. This method can scarcely be considered for portable instruments.

The photographic method of registration permits great increase in the indicator magnification by optical means with little friction loss. Therefore small masses are used. The apparatus is easily transportable, but the costs, especially with greater speed of registration, become very considerable if continuous registration is desired. The practice of combining extremely large masses with photographic registration is entirely useless in the present state of technique. Such large masses are also entirely unsuccessful for apparatus with which the short waves emanating from explosions are used for the study of the structure of the uppermost formations of the earth, since the wave lengths of the disturbance vibrations in the (perhaps still undifferentiated) mass are much smaller than the dimensions of this mass, so that complicated movements arise and the mass is no longer effective. In investigations of artificial tremors produced at definite times, the photographic registration with use of extremely light seismographs of very high magnification is superior to all others. Other possible methods of registration which might accidentally come into consideration, such as scratching on celluloid strips (see Wipple (1639)), chemical notation by a gas stream from a very fine point (see Belar (154), Laibach and Lumière (890)), or with ink from a very finely drawn-out glass-pointed pen on paper (Zeissig (1443, p. 449)), etc., will be only mentioned.

Measurement of Velocity.—To the second group of our division (p. 231), belong first of all the galvanometrically registering seismographs of Galitzin (496, 498, 499, 501, 503, 514), Ambronn (33*a*), and Reutlinger (613*d*, p. 593 *et seq.*). The galvanometric method of registration depends on the fact that a suitably formed coil, which is connected with a galvanometer, is displaced in a strongly magnetic field. The coil or the magnetic field is rigidly connected with the vibrating mass of the seismograph, the other part with the support. When the coil moves across the magnetic field, an electromotive force is induced in the coil which is proportional to the velocity of this movement. For investigations of natural earthquake phenomena with their proportionately long periods, registration with a mirror galvanometer of the D'Arsonval type has been successful. Navarro-Neumann (1157) also uses such an instrument. For tremor measurements of rapid, also for artificially excited, vibrations, a string galvanometer or an oscillograph, as shown, for instance, by Grunmach (587), is necessary (see also Meisser and Martin (1069*a*)).

The theory of the seismograph which registers by induced electric currents is likewise derived from the above-mentioned work by Galitzin. Reference may also be made to Gutenberg (1443, p. 462 *et seq.*), and to the description of Labrouste (887).

In this galvanometric (inductive) registration, friction is eliminated. The damping is regulated electromagnetically in the simplest manner. After conversion of the mechanical-vibration energy of the seismograph or tremor meter into a corresponding alternating electric current, the registration apparatus can be completely separated from the receiving apparatus. This is of practical importance in technical tremor meters and in seismographic apparatus for ground investigation. The concentration of the records of several tremor meters placed at different points, and all of various magnitudes of determination, on the film of a registration apparatus which is not itself sensitive to tremors, offers especial advantages.

In this group of tremor meters must be included the electromagnetic geophone, etc., as well as the submarine ground-signal receiver, on which there are reports by Stephenson (1481), Leighton (931), Ackley and Ralph (7). Patent papers of the Gesellschaft für drahtlose Telegraphie (534), of Siemens and Halske (1445), and Ambronn (31) describe the same kind of apparatus. With respect to the submarine sound receiver,

reference should be made to the descriptions of Hahnemann and Hecht (625), Du Bois-Raymond (201). These are extraordinarily clear and also very serviceable for the comprehension of the vibration processes in various tremor meters. Aigner (11) has made an exhaustive report on submarine sound technique. Such apparatus has been used by Fessenden (449), who, after von dem Borne (209), Belar (154*a*), Schmidt (1391*a*), next proposed the utilization of artificially excited seismic waves for earth investigation.

Measurement of Acceleration.—The acceleration of a body multiplied by its mass is equal to the force which brought about this acceleration. An equal and opposite force, acting simultaneously, can exactly annul the acceleration.

If the frame of a seismograph or tremor meter is displaced in sinusoidal vibrations with the period T' sec. and with the amplitude A, then the velocity v of this movement at any time t (neglecting friction) (see also Ambronn (33*f*)) is

$$v = \frac{2\pi A}{T'} \cos \frac{2\pi t}{T'},$$

and the acceleration a is

$$a = -\frac{4\pi^2 A}{T'^2} \sin \frac{2\pi t}{T'}.$$

The greatest velocities would therefore be reached at the times 0, $\frac{1}{2}T'$, T' . . . with $v_{max} = 2\pi A/T'$ that is, at the passage through the position of rest; and the maximum acceleration $a_{max} = 4\pi^2 A/T'^2$, at the times T', T' . . . , that is at the times of the greatest displacement. If the duration T of the natural vibrations of the tremor meter is large with respect to the disturbance period T', then the same values of v and a, but with opposite signs, hold good for the movements of its mass with respect to the frame.

The acceleration increases thus inversely with the square of the period of the disturbance, that is, acceleration meters are especially favorable for short period processes where small amplitudes may correspond to large accelerations. Therefore measurement of acceleration is preeminently suited for the investigation of the very short seismic waves which emanate from the detonation of high explosives. In this way extraordinarily high magnification of the amplitudes in comparison with those of the

ground movement (up to 100 million and more) (Ambronn (33*k*)) can be obtained in the recorded curves. Furthermore, such magnifications can actually be used in the practice of ground investigation, since the much longer period vibrations of the normal ground unrest are registered with very much slighter magnification and therefore recede entirely in the recordings. Every seismograph of the first or second group, according to the foregoing formulae, can be used for the derivation of the time path of the acceleration, for instance, the apparatus of Norton (1187), Norton and Warner (1188), Jahnke and Keinath (760), Jahnke and Heilmann (759), Heilman (679*a*), and Galitzin (516) although the accuracy of such a calculation is very slight.

A measurement of acceleration was first made by means of mercury surfaces of the oldest seismic instruments (see Ehlert (381)). When the instrument was subjected to a shock, *i.e.*, when it experienced an acceleration, the liquid flowed over the edge of a bowl (filled to the brim) on the side opposite that from which the impact came. The quantity of liquid which flows out gives a rough measure of the strength of the shock. With weak shocks on the surface, slight waves, which are observed directly or indirectly in the telescope, can also be registered optically on a moving strip of paper. Important investigations have been carried out with such a contrivance by Fouqué and Lévy (473), Milne (1106), and Noguès (1183). A similar solution of the problem of measurement of acceleration is offered in Schmidt's three-filament gravimeter (1392) for the construction of which reference is made to the literature.[1]

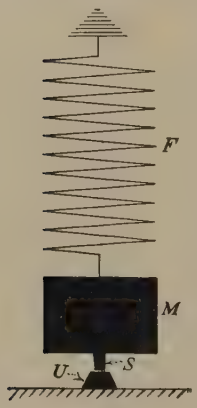


FIG. 77.

An immediate qualitative determination of an acceleration is obtained in the following manner: A mass M is suspended from a spring F (Fig. 77); at the point s the mass rests on the base U with the presssure $k = m \cdot g$ dynes. The force with which the mass M is attracted by gravity is $M \cdot g$ dynes, where g represents the acceleration of gravity. If the system experiences an acceleration a perpendicularly downwards, then the force with which the mass M presses on the base is diminished $M \cdot a$ dynes. As soon as $M \cdot a$ becomes smaller than $k = m \cdot g$, the pressure

[1] The apparatus of Reeh (1278) is mentioned only for the sake of completeness. Its practical utilization appears very doubtful.

of the point s on the base U ceases and the mass M is lifted off. At the limiting acceleration a_o, where the pressure k on the base just disappears, $a_oM = m \cdot g$ or $a_o = m \cdot g/M$. The mass M is determined by weighing. On the other hand, m indicates the weight which must be hung on a spring fastened to M, carried vertically upward over a roller and downward again, in order just to raise from the base the point s in a system at rest. Practical models of this kind of contrivance are described by Grunmach (587, 588), Mainka (1035, p. 244 *et seq.*), Auclair and Boyer-Guillon (70), and in an especially suitable form for technical use by Ambronn (33*f*). Electrical contact is made between the points and the base. When the acceleration exceeds the limiting value a_o, this contact is broken by the lifting of the point s from the base. A time registration can be made by a string galvanometer (see Grunmach (587) and Ambronn (33*h*, *k*)), in which the place of observation can be separated from the place of erection of the acceleration meter. This is often of great practical importance. The support-pressure k can also be regulated at a distance electromechanically or purely electromagnetically (33*h*, *k*), so that the receiving instrument can be made water-tight, as Grunmach (588) has done. Similar contrivances can be made for every other direction of acceleration. For very small accelerations, the changes in the elasticity of the spring (and thus the support pressure) with the temperature, etc., must be taken into consideration, as Ambronn (33*h*, *k*) has done in practice. By repetition of the measurement with alternating limiting accelerations or with individual elements adjusted step-like to several different limiting accelerations, each acceleration may be determined with the requisite accuracy (*cf.* 1035, p. 245). Measurement of the pressure and its variation with time can be obtained by microphone contacts, by piezoelectric crystals, by use of optical double refraction, through strained isotropic plates, etc. It is important that acceleration curves can be obtained quantitatively from the equation $p = m \cdot a$, with apparatus in which there are no parts movable with the measurement. The pressure measurements must always follow a principle in which no perceptible displacement appears at the place of pressure. Mechanical-lever arrangements are impossible and always lead to false results. For this, however, no damping whatever is necessary as it was in the first two groups. This is a great advantage for measurements of acceleration.

A modern contrivance for observing ground vibrations on the principle of measurements of acceleration, after Ambronn, is shown in Figure 77A. The water-tight chest S contains the acceleration meter (mass = 150 gr.), which converts the acceleration curve quantitatively into a similar electric-current curve. The switch board T is connected to six seismographs erected in the field in suitable arrangement and connected by light cable conductors. They serve simultaneously for regulating and registering, or for standardizing the sensitivity of the seismograph

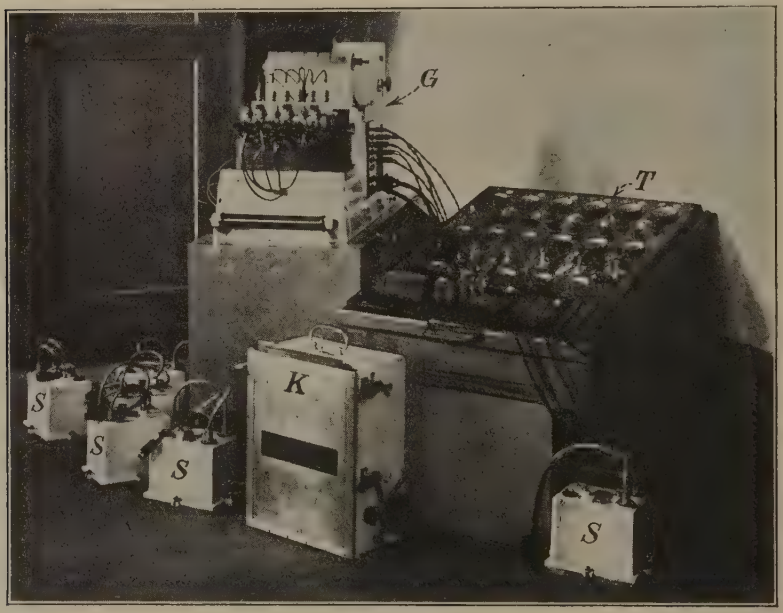


Fig. 77A.

as given above. This sensitivity can be changed in the most convenient way by remote control in the proportion of 1 to more than 10,000. A string galvanometer G with six string systems registers the six curves on a common film together with the moment of the explosion on the same time scale. In this way are created the most favorable conditions conceivable for accuracy of measurement and also for the possibility of clear comparison. K is the exchangeable film holder in which the film can be passed with a velocity of 5 to 100 cm. per second. The movements of the strings during the survey itself are to be controlled

at the switchboard. Several small storage batteries suffice for the operation of the apparatus, which is readily transportable on a small truck. Figure 77B shows the registering apparatus mounted on such a small truck.

FIG. 77B.

Standardization of Seismographs.—In order to have at disposal safely adjustable vibration movements of the whole apparatus of accurately known amplitude, period, or vibration form, for testing the vibration properties of seismometers or tremor meters at chosen times, special test plates have been prepared which can give the desired movement by means of suitable contrivances and on which the instrument to be tested can be placed. Such test plates have been built by Omori (1197), Galitzin (504, 508, p. 26 *et seq.*, 515,), Mainka (1031). In order to understand thoroughly the characteristics of the individual tremor meters, it should never be neglected to test them most carefully on a reliably built test plate for the entire range of periods and amplitudes for which they are to be used.

On the basis of the knowledge of the instrumental constants (individual periods, indicator lengths, damping, and friction) it is then possible to derive the true ground movement itself from the three components shown by the seismograph or tremor meter. Since the calculations necessary for this are very complicated in general form, this work is seldom done. It is considerably simplified if the individual disturbance waves to be analyzed can be represented as pure sinusoidal vibrations or considered as such with sufficient approximation (see also Galit-

zin (513)). In relation to the methods used in this, reference may be made to the works of Sekija (1429), Arnold (58), Klotz (815), and Gutenberg (613*d*, p. 234 *et seq.*).

The Extension of Artificial Tremors in the Ground, and Seismic Ground Investigation.—By explosions, the fall of weights, industrial movement of masses, etc., earth tremors are produced whose time and place, strength and variety, are exactly known or can be chosen for the special purposes of an investigation. The utilization of earth waves emanating from such disturbances therefore offers an especially favorable medium for the determination of the velocities of elastic waves in different kinds of ground and rock, and for the analysis of the geologic structure of the uppermost zones of the earth.

Earthquakes excited artificially by explosions were first used by Mallet (1041) to measure the speed of propagation of elastic waves in different kinds of rock and soil. Abbot (2) worked in a similar direction with very large charges of explosives; Milne (1106, 1115) produced tremors by means of falling weights; Fouqué and Lévy (473) and Noguès (1183) have also carried out comprehensive investigations of this kind. The results of these older works are rather ambiguous, however; there usually seems to be insufficient distinction between the longitudinal advance waves and the surface waves which follow later and often have much more powerful effects. The receiving measurements were usually carried out with a mercury-mirror seismoscope. The time of sending was reckoned back from the time of reception of sounds through the air, which naturally can never give accurate data.

Noguès (1183) also used underground explosions and determined the difference of the velocities parallel and perpendicular to an ore vein. He then called attention to numerous conditions which influence the wave velocity in the subsoil: the kind and composition of the rock, its molecular state, the orientation of the mineral masses, the manner of the deposition, their density, their water content, the position of the wave surfaces, and also the kind of tremor itself.

Most careful investigations of the velocity of propagation of elastic ground waves resulting from explosions have been carried out by Hecker (658) on the sand of the practice grounds of Cunnersdorf. Conical pendulums of 2 kg. weight which registered on sooted glass discs, served as receiving apparatus.

He found 1,430 m. per second as the speed of propagation of the longitudinal waves produced by the first impulse, 238 m. per second for the surface waves of greatest amplitude. The influence of the subsurface structure also was noticed. Wiechert (1612) reports that the velocity of the main (surface) waves in the sand of the practice ground at Meppen was 240 m. per second. The measurements were made with a tremor meter magnifying 50,000 times, which could detect the step of a man at 100 m. distance, a herd of sheep at 500 m., and a railroad train at 10 km., and which was therefore exposed to undesired disturbances in especially high degree.

From the theoretical side von dem Borne (209) shows the great importance of seismic investigations by artificial elastic waves for geologic exploration of the uppermost formations of the earth when he writes:

> As the observations of seismic phenomena afford us a clue to the mechanical relations of the earth and indeed first to the, geologically speaking, deep-lying portion of the same, so also do they give us corresponding explanations on the tectonically more important portions near the surface. Above all, the instrumental study of slight local quakes, of artificial disturbances and ground movements of meteorological origin, should be linked together here.

Galitzin also emphasizes in his "Vorlesungen über Seismometrie" (514, pp. 196–7) the practical importance of investigations on the propagation of artificially excited elastic waves in the subsoil.

Mintrop (1118) sought to use methods of determining the focus of earthquakes from the time path of the earthquake waves to ascertain the place of artificially excited earth tremors, for instance of artillery grounds. For this purpose he constructed his tremor meter described on page 237. The practical execution of this method is defeated, however, by the fact that the shots must fall very sporadically in order not to make the general ground unrest too great, and that the discharge of a modern gun with recoil chambers transmits a much slighter amount of energy into the subsoil than the shock of an explosive projectile, especially such a one with a delayed fuse.

The principal obstruction to this method, however, is the very great difference in speed of propagation of the elastic waves in different soils. This varies from several hundred to about 6,000 m. per second. This hindrance is changed into just as great an advantage if the problem is reversed, and, according to

Fessenden (449), Mintrop (1120), and others, the observed wave velocities at known distances between places of explosion and the recording apparatus are used in suitable manner for the determination of the unknown geologic structure of the subsoil.

Fessenden (449) used submarine sound transmitters as the exciters of the tremor waves. He also sank these transmitters in wells to desired depths (see also Heiland 674). Sound receivers which could be lowered to the requisite depths in wells were arranged as receivers. The registration of the incoming tremor waves, as well as the time of sending of the waves was made by means of string galvanometers. The use of membrane sound transmitters and tuned submarine sound receivers, on the principle of the telephone, has the added disadvantage that the onsets, depending on the damping of the system, are more or less indefinite. How far this method may be actually carried out in practice, however, must remain undecided.

In close connection with the work of Wiechert and his students on the relation between the formational structure of the interior of the earth and the form of the time-distance curve, as already proposed by Schmidt (1391*a*) and Bélar (154*a*) (1425*b*), Mintrop (1120) turned the time-distance method with use of artificial elastic waves to the analysis of the formational structure of the uppermost crust of the earth. By this it was proved that the formational boundaries are generally very sharply defined in nature. Thus in many cases extensive formations with very different wave velocities bound one another, while within these formations, because of the long times during which there were essentially similar conditions of sedimentation, the wave velocities remain almost constant.

One tremor meter used for registering these measurements is described on page 237. In general, however, just as the apparatus used by Angenheister (51*c*) and Schweydar and Reich (1425*b*), it can be used to give the time of arrival of only those elastic ground waves which, emanating from the explosion focus, are the first to reach the receiving place along any path through the ground. In homogeneous regions, the longitudinal waves possess the greatest speed of propagation. On the basis of certain observations, however, it seems questionable whether in stratified ground the first incoming tremor waves possess a purely longitudinal character during their entire course in the subsoil.

If an explosion center S is arranged in a region with homogeneous subsoil with similar wave velocity in all parts and in all directions, and a tremor receiver E is set up at the distance a from the explosion center, and if t equals the time elapsed between the moment of the explosion and the incidence of the waves excited by it on the tremor meter, then the fraction a/t gives the velocity of the most rapidly traveling (longitudinal) waves.

Special attention must be given to the establishment of the time of the excitation of the elastic waves at s. Rothé (1306) treats this question exhaustively. The time of the excitation of the elastic ground waves is reckoned backward from the time of the arrival of the sounds through the air, which are produced at S simultaneously with the elastic waves in the ground. This can only be looked upon as a very crude and extremely risky makeshift. The wave velocity in the air is as small as $\frac{1}{20}$th of that in the ground, so that the error in taking the running-time of the sound waves through the air for calculation of the wave velocities in the subsoil must be magnified proportionately up to twenty times. The determination of the time of the explosion by means of the light of the flame produced by the explosion, which Mintrop (1120) proposed, may be very difficult technically and the entire method limited in time (to night) and in space (to very open country between S and E), in a manner which is practically inadmissible. The superficial arrangement of the explosives requisite for this also is disadvantageous, since (see Hubert (747)) the strength of the tremor waves produced by the detonation of a charge of explosives is increased by deeper burial 50 to 100 times over its explosion at the surface. This disadvantage is avoided if the time of the explosion is transferred by telegraphic or wireless conduction to the receiving apparatus. A suitable adjustment must be made for these signals, which is not an easy matter in mechanical tremor meters. Electromagnetic or electric tremor meters are therefore to be preferred for the carrying out of seismic ground investigations.

Seismic methods are especially suited for the investigation of the tectonic structure of a stratified subsoil. An example may illustrate this better (see also Meisser and Martin (1069*b*) and Schweydar and Reich (1425*b*)). Under an upper cover of unconsolidated rocks, perhaps sandy clays, with the wave velocity v_1, there lie formations of a harder rock, perhaps hard limestone, with a wave velocity v_2. Next, a charge of explosives

is set off at S (Fig. 78), and the arrival of the tremor waves registered on a series of tremor meters placed in a straight line, for instance 200 m. apart. In the time-distance curves recorded by the tremor meters, then, the running-times belonging to each basic length are entered as ordinates. At E_1 the running time corresponds to v_1, similarly at E_2; from this point on, however, the waves which run through the lower medium with the higher wave velocity v_2 arrive at E earlier. The speed of propagation along the surface of the earth, then, from E_2 on is equal to v_2 the wave velocity in the deep formation. The time-distance curve has a break at K. The wave velocity v_1 in the upper formation is

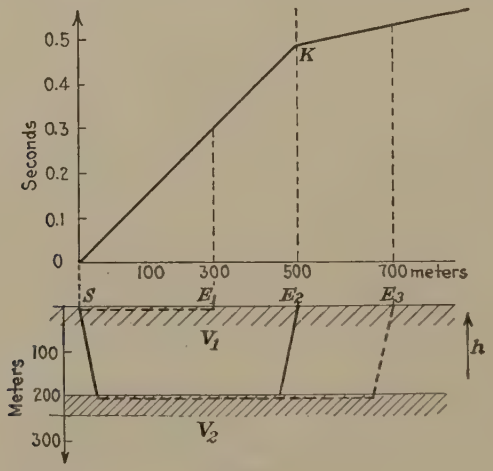


Fig. 78.

obtained from the portion of the time-distance curve before the break, the wave velocity v_2 in the lower formation from the portion after the break. The position of the breaking point gives the perpendicular distance h from the surface of the earth to the bounding surface of the hard formation. In our example, as is recognized at once, $v_1 = 1{,}000$ m. per second, $v_2 = 5{,}000$ m. per second, and $h = 200$ m. For inclined formations and for several superimposed formations, there would be corresponding curves, the individual representation of which would lead us too far here. Heiland (674), Gutenberg (613*d*, p. 597), Mintrop (1120), Seismos (1428), Reich (1287, 1289), Ambronn (28, p. 39 *et seq.;* 33), Inglada (769), Meisser and Martin (1069*b*), give theoretical and practical examples of this kind of calculation.

In practical work in the field by seismic methods of investigation, it has been shown long ago that this method of calculation according to the principle of the bounding ray gives false results, and that it is better to carry out the calculations under the assumption that the energy transference or the sharp onset in the seismogram follows along rays which are perpendicular to the bounding surfaces between the different ground formations. In most recent times these methods of evaluation of the seismogram have been published by Schweydar (1425*b*).

Aside from the better approximation of the results, in reality this manner of calculation also has the advantage of notably greater simplicity and rapidity. A strong theoretical basis for these characteristic relations of the main rays is not known at present, but, according to Jeffreys (762*f*), it can be assumed that the energy is transmitted along the bounding surface in the form of bounding-surface (upper surface) waves with the velocity of the longitudinal waves in the formation with the higher speed of propagation.

The time-distance curves for a number of characteristic topographies are given in Charts A–D. The structure section near the position of the base line is shown above, and the two path-time curve systems are shown below; the solid curves belong to the representation of a seismograph at the left end point of the base from which the place of explosion is removed toward the right, while in the broken curves it is assumed that the seismograph stands at the right end of the base and the place of explosion moves from right to left. For the sake of better comparison and interpretation of the curves, however, in the time-distance curves the distance (abscissae) always go from left to right.

In Chart A a horizontal deep formation is assumed at the depth h_1. The path-time t_2 of the deep waves is

$$t_2 = \frac{2h_1}{v_1} + \frac{e}{v_2}.$$

If the distance e of the explosion from the seismograph is changed to Δe, then

$$t_2 + \Delta t_2 = \frac{2h_1}{v_1} + \frac{e + \Delta e}{v_2}.$$

Thus:

$$\Delta t_2 = \frac{\Delta e}{v_2}; \; v_2 = \frac{\Delta e}{\Delta t_2}.$$

The speed of propagation v_2 in the deeper formation is thus equal to the velocity with which the waves coming from the depth advance along the ground. The depth h_1 at which the bounding surface lies, is obtained very plainly if the curve t_2 is lengthened to the ordinate axis, *i.e.*, $e = 0$. Then

$$t_2' = \frac{2h_1}{v_1},$$

$$h_1 = \frac{t_2' \cdot v_1}{2}.$$

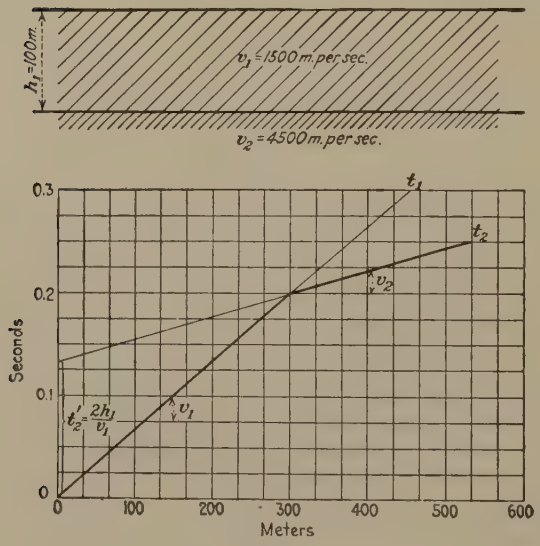


CHART A.

But v_1 follows from the time between the explosion and the entrance of the waves (t_1) moving in the upper medium, while t_2' can be derived at the point of intersection of the t_2 curve with the ordinate axis in the time-distance curve.

Chart B shows the same thing for a system of three formations with the velocities $v_1 < v_2 < v_3$, while the thicknesses of the uppermost and the middle formations are h_1 and h_2.

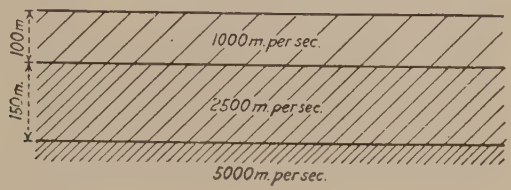
For t_1 and t_2, *i.e.*, the time of passage through the two upper formations, the same relations hold as above. On the other hand,

$$t_3 = \frac{2h_1}{v_1} + \frac{2h_2}{v_2} + \frac{e}{v_3}.$$

In exactly the same way as above, it is found that

$$v_3 = \frac{\Delta e}{\Delta t_3},$$

that is, the speed of propagation in the middle, and likewise in the deepest, formation is equal to the speed of propagation of waves returning along the surface of the earth from the upper boundary of the medium in question.



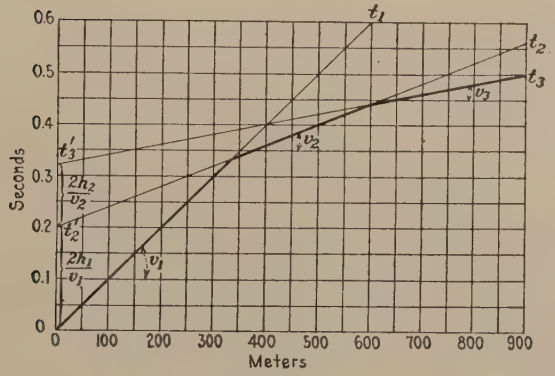


CHART B.

Here h_1 and h_2 also can be obtained without further trouble from the path-time curves if the curves t_2 and t_3 are prolonged to the ordinate axis. Since t_2 cuts off from the zero point a portion

$$t_2' = \frac{2h_1}{v_1},$$

$$h_1 = t_2' \cdot \frac{v_1}{2},$$

while t_3 cuts off from the point of intersection of t_2 with the ordinate axis a further portion

$$t_3' - t_2' = \frac{2h_2}{v_2},$$

from which it follows that

$$h_2 = (t_3' - t_2') \cdot \frac{v_2}{2}.$$

Chart C shows the running-time for a formation dipping obliquely at the angle α and for the case of shooting in the opposite direction.

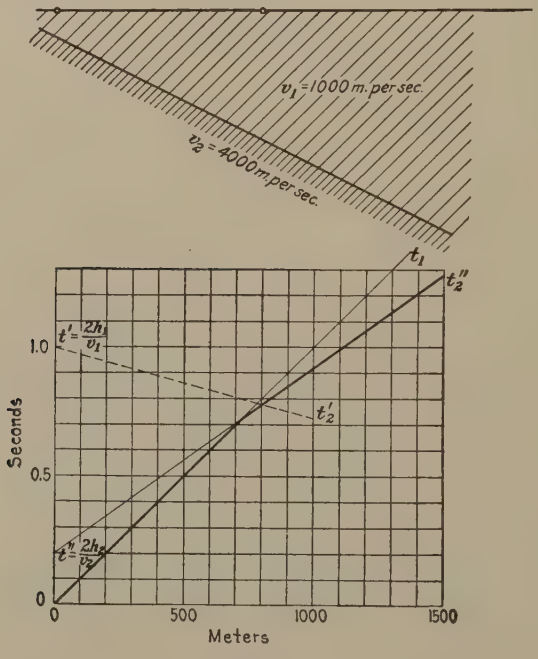


CHART C.

If h_1 and h_2 are the perpendiculars from the end points of the base d to the upper surface of the deep formation, then the time-distance t_2 of the deep waves will be

$$t_2 = \frac{h_1 + h_2}{v_1} + \frac{d \sin \alpha}{v_2}.$$

If now the seismograph is moved the distance Δd to the right or the explosion point, the space Δd to the left, then there are obtained the new time-distances t_2' and t_2'':

$$t_2' = \frac{h_1 + h_2 - \Delta d \sin \alpha}{v_1} + \frac{(d + \Delta d) \cos \alpha}{v_2},$$

$$t_2'' = \frac{h_1 + h_2 + \Delta d \sin \alpha}{v_1} + \frac{(d + \Delta d) \cos \alpha}{v_2}.$$

If the value of t_2 is drawn from these two equations, then

$$t_2' - t_2 = \left(-\frac{\sin \alpha}{v_1} + \frac{\cos \alpha}{v_2} \right) \Delta d,$$

$$t_2'' - t_2 = \left(\frac{\sin \alpha}{v_1} + \frac{\cos \alpha}{v_2} \right) \Delta d.$$

Dividing through by Δd, there are obtained for the reciprocal values of the apparent velocities, v_2' and v_2'' on the basis of shooting and then shooting in the opposite direction, the values

$$\frac{1}{v_2'} = -\frac{\sin \alpha}{v_1} + \frac{\cos \alpha}{v_2},$$

$$\frac{1}{v_2''} = \frac{\sin \alpha}{v_1} + \frac{\cos \alpha}{v_2}.$$

v_2' and v_2'' follow from the corresponding time-distance curves t_2' and t_2'' as cotangent of their angle of inclination; v_1 is known from the cotangent of the angle of inclination of the curve t_1, so that α and v_2 can be calculated from the equation given above. If the abbreviations are taken.

$$\frac{1}{v_2''} + \frac{1}{v_2'} = m,$$

$$\frac{1}{v_2''} - \frac{1}{v_2'} = n,$$

then

$$\sin \alpha = \frac{n \cdot v_1}{2},$$

$$v_2 = \frac{\sqrt{4 - n^2 v_1^2}}{m}.$$

The distances h_1 and h_2 follow at once from the time-distance curves when the time-distance curves t_2' and t_2'' are prolonged to the ordinate axis. The ordinate intersection τ' and τ'' then become

$$\tau' = \frac{2h_1}{v_1},$$

$$\tau'' = \frac{2h_2}{v_1},$$

and

$$h_1 = \frac{\tau' v_1}{2},$$

$$h_2 = \frac{\tau'' v_1}{2}.$$

The position of the bounding surface between the two formations with the wave velocities v_1 and v_2 is not yet absolutely determined. For this there is needed still a third distance h_3 from the end point of a base line beginning at 1 or 2 and running obliquely to d. The bounding surface (as a plane) is then taken as the tangential plane of the points 1, 2, 3, with the radii h_1, h_2, h_3, of the surrounding spherical surfaces which can be obtained by calculation or graphically.

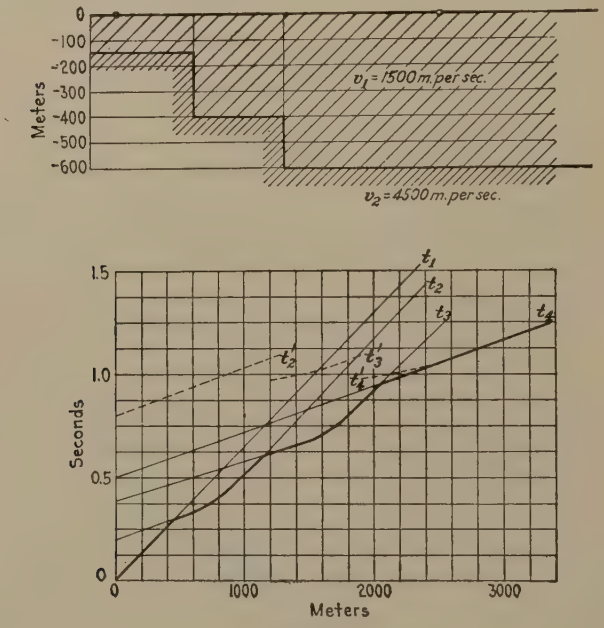


CHART D

Finally, Chart D shows the form of the time-distance curve obtained by shooting and counter-shooting over a subsurface consisting of two media with the wave velocities v_1 and v_2 sunk in terraces. It is assumed that the boundary is horizontal. The calculations are self-apparent from above.

Of the valuation of transverse waves, etc., which emanate from artificial earth tremors, nothing is known as yet. The receiving apparatus used in the field at present are scarcely suitable for resolving the apparatus vibrations following the first onset, so that the times of arrival of the later and definitely characterized wave trains can be derived with sufficient accuracy.

Figure 78A shows three seismograms which were taken by Ambronn's acceleration meter, in which the individual onsets seem sharply separated, and in which the usually disturbing air vibrations of the sound are generally lacking. A detonator was exploded at distances of 110, 130 and 150^m. The subsoil consisted of foliated siliceous chalk of the Triassic.

Reflected waves still cannot be detected with certainty in investigation by explosions.[1] It should seem that the measurements of Mothes (1137*a*) on a glacier, where conditions were especially favorable for the observation of such reflected wave

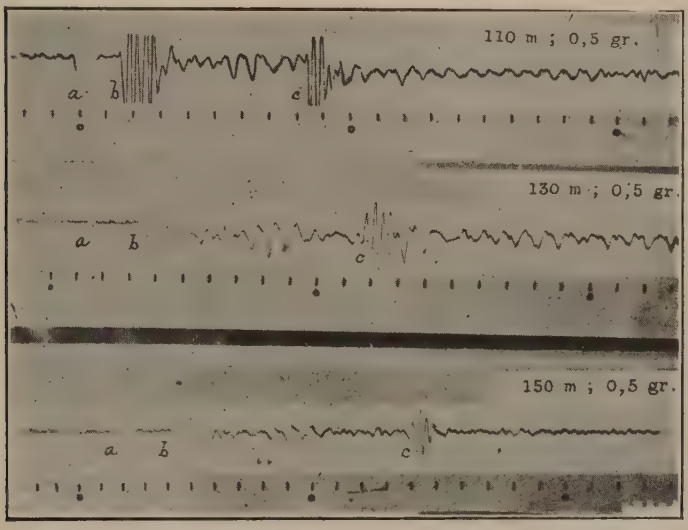


FIG. 78A.—*a*. Explosion signal. *b*. First waves. *c*. Surface waves.

trains because of the elastic homogeneity of the upper formation (the ice), may also be made by the above-designated time-distance method, so far as the rather incomplete publication of the observation data makes a check possible.

Nothing has yet been made public on such investigations on the velocity of the propagation of the elastic waves in the uppermost formations of the earth. Attention, however, is directed to the data on page 246 on the scientifically worked-out local

[1] A technique for the detection and use of reflected waves has been perfected and is in practical application in the seismic work in Texas and Louisiana. No data in regard to it are available in the literature. THE TRANSLATOR.

quakes and accidental explosions. In any case, the petrographic condition, not the geologic age, determines the elastic properties of the rock.

The following most important data have been taken from the literature on observations of local quakes and intentional or accidental explosions.

In the Aachen district, Haussmann (645) found $V = 6.0$ km. per second. for distances of 150 to 200 km., and $V = 6.7$ km. per second for 400 km. parallel to the strike of the formation, but 5.0–5.5 km. perpendicular to the strike. v varies less, the corresponding numbers being 3.4 and 3.6 or 3.5 and 3.6 km. per second. Errulat (424) found $V_m = 750$ m. per second for surface waves at a distance from the explosion (over tillite) at Rothenstein. From the same source it was found that $V_m = 625$ m. per second in the explosion over loam and loess at Steinfeld, near Vienna, and in a local quake at Sophia $V_m = 650 - 750$ m. per second.

The propagation of the tremor waves which were produced by the explosion at Oppau on September 21, 1921, have been exceptionally well worked out. According to Zeissig (1661), the fastest waves in the uppermost formation have a velocity of 5.5 km. per second; Hecker (668*b*) found $V = 5.73 \pm 0.4$ km. per second and $v = 3.0$ km. per second; Wrinch and Jeffreys (1648*a*) give $V = 5.4$ km. per second. Krumbach (873*a*) also gives a formula for the dependence of the speed of propagation upon the distance. Gutenberg (601) finds $V = 5.6$ km. per second at the surface of the earth and $V = 5.9$ km. per second for a depth of 60 km., from the combination of this explosion with observations on central European quakes. Below 60 km. depth, V rises to 8.0 km. per second, while simultaneously $v = 4.3 \pm 0.2$ km. per second close below this boundary of instability. A new calculation of the results of the observations on the Oppau explosion is given by Gutenberg (612). Here the average elasticity constants for the formations traversed are also derived. Meissner (1073) treats especially the increase in velocity with depth of the earthquake waves excited by the Oppau explosion. Inglada (770*b*) finds a velocity of 5.5 to 5.6 km. per second in the primordial rocks for the longitudinal waves emanating from the Oppau explosion.

There are reports by Rothé (1307) and Maurain (1060) on the results of observations on earthquake waves excited by the

explosion of La Courtine; they give for V about 5.6 km. per second for the surface waves V_m about 2.8 km. per second. From some great blasts near Malancourt, Rothé, Lacoste, Bois (1306*b*), found $V = 5.7$ km. per second for 5.2 km. local distance. Wiechert (1614) found across the Leine valley, from the survey of a blast at about 17 km. distance, $V = 4.8$ km. per second. De Quervain (1261) also finds as the apparent velocities of propagation of the explosion waves from a blast in Alpnach and an explosion at Spezia: for the longitudinal waves at the focus 4.5 km. per second, and at 400 km. distance from the focus 6 km. per second. From his observations with very small focal distances, at Hainberg, near Göttingen, Hubert (747) derived a velocity for the longitudinal waves of only 1,700 m. per second. On the basis of his observations on local quakes, Mohorovicic (1123, 1127) gives $V = 5.54$ and 5.60; $v = 3.2 - 3.3$ km. per second. Conrad (316*b*) finds for the Tauern quake of November 11, 1923, $V = 5.43$, $v = 3$ km. per second. A large number of such velocity values have been compiled by Gutenberg (613*d*, p. 279 *et seq.*).

The values given in the literature for velocities in the rocks of the uppermost formations of the earth which are especially interesting from a geological standpoint, are much too small (and, indeed, often apparently so), because the seismographs used were not sufficiently sensitive to allow the first onsets to be recognized. This is true, for example, of the value 3,500 m. per second, which Schweydar and Reich (1425*b*) give for gypsum, of the value 2.14 km. per second for chalk, which is found in Maurain and Eblé (1059*a*). On the other hand, Angenheister (51*c*) gives for gypsum the nearly correct value of 4,500 m. per second. The data of Gutenberg (613*d*, p. 608) almost all are too small.

On the basis of most comprehensive practical experience, Salfeld gives a survey of the elastic relations of the rocks of the uppermost crust of the earth, which shows that these may be divided, according to their petrographic condition, into several groups within which the wave velocities vary only slightly:

1. 600 to 800 m. per second: rubble, gravel, sand loess (when very wet V up to 1,200 m. per second).
2. About 1,800 m. per second: clay, clayey sandstone.
3. 2,200 to 2,400 m. per second: slightly calcareous marl, siliceous sandstone, slightly calcareous sandstone.

4. 3,200 to 3,800 m. per second: calcareous marl, calcareous sandstone, hard clay slate.

5. 5,000 m. to 6,200 m. per second: limestone, dolomite, gypsum, anhydrite, salt, metamorphic rocks, massive rocks.

Milne (1106) and Benndorf (165) proposed to measure the apparent angle of emergence in artificially excited earthquake waves, in order to compare it with the true angle of emergence calculated from the time-distance curve. The emergence angles of the forerunner of artificial earthquake waves, measured with sufficient approximation by Schweydar and Reich (1425*b*), show, however, that the waves come vertically from below at relatively slight distances from the point of explosion. Measurements of the angle of emergence in regions with a strongly inclined, harder, deep formation, would be of greater importance in this respect. This would determine whether the waves always move at right angles to the surface of the earth, or whether, as is required in the hypothesis given above, they move toward the surface of the earth at right angles to the upper surface of that deeper bed.

Important data in regard to the form of the deposits in the subsoil or on the thickness of the strata can be obtained from the individual vibrations or waves arising in them (see Merten (1087*b*), Wiechert (1615*a*)). With seismic waves caused by impact, these should be evident as marked wave trains in the seismogram (with use of suitable tremor meters), as Hubert (747) and Brand (235*a*) have shown. From the instrumental and statistical point of view, as well as on geological principles, the greatest care must be exercised in the acceptance of over vibrations. However, from the most recent observations on surface waves very rich in energy, which advance with very low velocity, it seems very doubtful whether perpendicular (upright) waves or those from deeper formations can be separated by jerky or rhythmic excitation. With excitation of the ground movement by periodic waves, the sources of these waves, perhaps also the individual vibrations of such chance objects in the subsoil, can be detected, according to a proposal of Ambronn, if the dependence of the receiving intensity is determined upon the period length of the elastic waves sent out. If bodies with an individual vibration period (mechanical resonators) are present in the subsoil, the phenomena of resonance and absorption effects must be noticeable unless they are overlain by the slower

surface waves. The study of the distribution of this influence according to kind and strength along the surface of the earth can perhaps yield information on the position of such deposits.

The production of elastic waves by periodically vibrating transmitters, somewhat after the manner of the submarine sound transmitter, by unbalanced revolving masses or the like, does not yield clear onsets on the receiving instruments. Perhaps it may eventually be possible, as the determination of direction of the elastic waves in the water by submarine sound receivers or in the ground by geophones is already customary, to establish the position of wave surfaces by surveying with two receiving apparatus, one of which is moved along on the ground until the vibrations received by it are found in the same phase with those received by the other. This method has proved excellent in submarine sound signals, and seems to be applicable also to the location of hammer signals from mines by use of acoustic or electromagnetic geophones. Nothing is known at present of attempts at application of this principle to the problems of geoelastic ground investigation.

The use of seismic methods in practical geology are manifold. Unfortunately, in the present publications, for example (1428), there are almost no technical data and no information on the degree of accuracy obtained. Some illustrations from these publications may be given here as examples of the problems which can be solved by seismic means. Recently Weigelt (1593*a*) and Kithil (810*a*) have illustrated the application of seismic methods by various examples. In Meisser and Martin (1069*b*) are found examples of observations, which, however, are still treated according to the older methods of calculation by the entrance of rays from the deep formation. Schweydar and Reich (1425*b*) give some practical examples.

The problems to be worked first are those in which the depth and the dip of formations are to be determined, where the deeper formation shows a higher wave velocity than the one above it. For this, the angle of dip for the different formations (1428) need not be the same, as Figs. 79 and 80 show. In favorable cases, however, the depth, thickness, and dip can also be determined for formations which show a lower wave velocity than the formations above them. If the formations are cut by a fault, then the position and amount of throw of the fault may be determined by seismic measurements parallel to the fault, or crossing its base line.

In such measurements, accuracies within 1 to 2 per cent have already been obtained in the depth data, while the angle of dip can be derived to within ½°. In all problems of oil geology where it is a question of the search for domes or anticlines, and thus the determination of the angle and direction of dip of the formations, the high accuracy of the seismic methods of measurements is of especial importance.

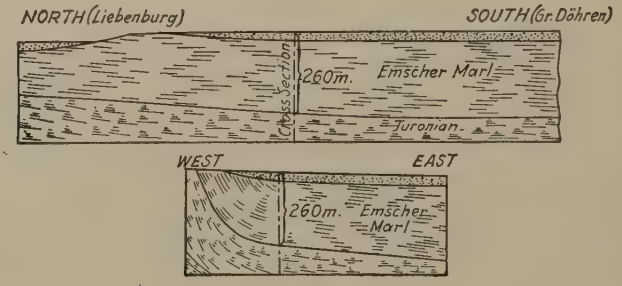


FIG. 79.

The same thing applies to seismic investigations in coal regions. This is especially true if the productive formation, as for example in Holland, is buried beneath thick formations of younger rocks with lower velocity, and localities must be sought where horsts have raised the coal formation to lesser depths suitable for economic development.

The investigation of buried salt domes offers the most acceptable problem for seismic methods of prospecting. Here the

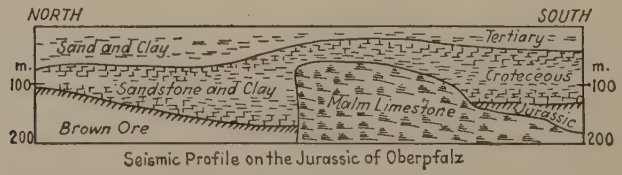


FIG. 80.

depth and shape of the dome, and even the inclination of its flanks, may be determined. Because of the very slight density of salt, gravity measurements along characteristic sections (chosen, however, from seismic data) are often valuable in combination with the seismic investigation. Finally, electrical measurements can be used to locate the film of highly conducting salt water which surrounds the salt dome.

Some possibilities of application are also offered in lignite mining, where the slight depth usually requires only weak charges of explosives and simple apparatus. Further, seismic investigations are suitable for testing the uniformity and stability of the subsoil in deep and high technical projects.

In the search for underground water, seismic methods can also be advantageous if explanation of the structure and knowledge of the dip of the formations and of the position of the faults

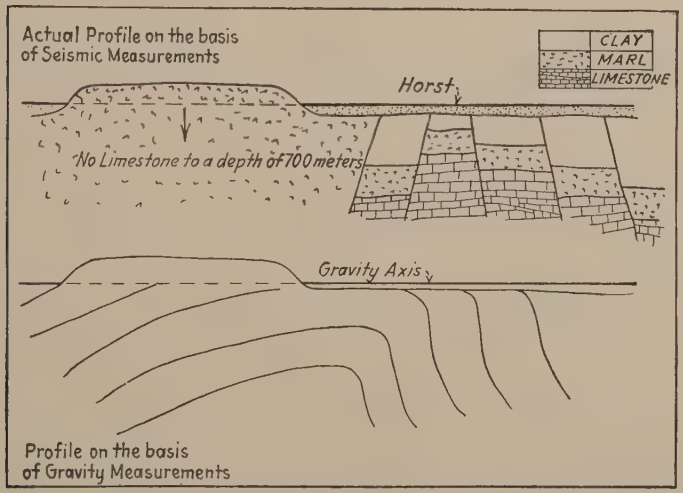


FIG. 80A.—Comparison between the results of gravity and seismic investigations in the same regions.

can contribute to this. The same thing holds for the development of ore deposits in veins and layers. The ore itself generally cannot be detected directly by seismic means, unless it is an especially massive formation. In numerous cases, however, the correct localization of the accompanying formations with marked wave velocity or of ore-bearing fissures or zones is of far-reaching importance. In just such problems the appropriate combination of the seismic methods with other suitable physical methods of prospecting, especially electrical and magnetic measurements, can be of considerable advantage. There must still be mentioned here the problem of the search for earthy ores in pockets in a hard calcareous basal formation. Mothes (1137*a*) has measured the thickness of a glacier by seismic methods and obtained good results, although one cannot entirely agree with his methods of

calculation. These may cause very little change in the results, however.

In the erection of buildings designed to withstand earthquakes, the accurate investigation of the processes in the passage

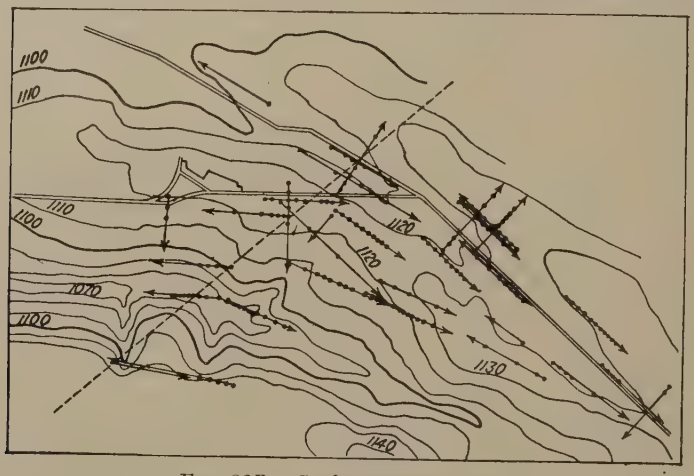


FIG. 80B.—Surface contour map.

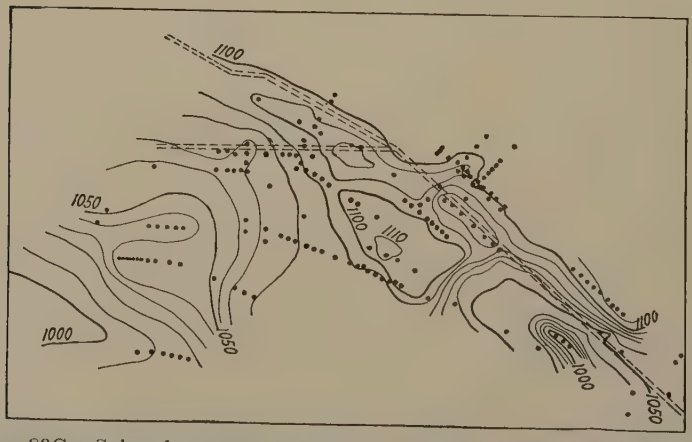


FIG. 80C.—Subsurface map, contoured on gneiss, made on the basis of seismic investigations. → Direction of shooting. • Points where measurements were taken.

of earthquake waves and the relations of the uppermost formations of the earth are of the greatest interest, in order, by suitable construction, to avoid, or lessen as much as possible, the damage from these. The maximum acceleration which the waves pro-

duce, determines the amount of such damage. Resonance phenomena and period length also can be of great importance, since the greatest amplitude of vibration of individual parts of the building is increased in proportion to the acceleration. The basic points of view for such investigations are treated by Milne (1108, 1111), Omori (1197), de Montessus de Ballore (1134), Galitzin (501), Kusakabe (884), Schmidle (1373), Polescjuk (1245), Graatz (576), Hadley (622), Inglada (769), Alvarez (22*a*), Obata (1188*b*), Dewell, Andrews, Mauwaring (346*a*), and others. Frech (486) also has investigated the influence of the secular changes in seismic activity on the historic development of architecture. Hunt (754), Summers (1498), Lais (892), determined a considerable influence of the number of stories in buildings on the effect of quakes.

The possibility of predicting earthquakes has often been treated without obtaining any practical results. Hobbs (724), Galitzin (514, p. 211 *et seq.*), Hodgson (727), Jones (789*a*), and others have studied this question. The investigations on the question as to whether gas outbreaks or rock falls may result from earthquakes are also important in mining. After Milne (1113) had already worked on the influence of the seismic ground unrest on fire-damp accidents, statistical compilations of von dem Borne (210) and Mintrop (1117) denied any connection (see also Simcock (1447*a*)). Strong vibrations from shooting, according to Kirst (810), can release threatened gas outbreaks.

CHAPTER VIII

THE DISTRIBUTION OF TEMPERATURE IN THE EARTH'S INTERIOR AND THE USE OF TEMPERATURE MEASUREMENTS IN APPLIED GEOPHYSICS

Measurements of the increase of temperature with depth were first made in mines at the beginning of the nineteenth century. Later investigations in deep borings, however, yielded more reliable results. D'Aubuisson (68), von Trebra (1546), Forbes (468), Fox (475), Moyle (1140*b*), and others collected data from mines in Germany and England. Forbes (468) discusses all possibilities of heat development in mines due to light, blasting, presence of man, etc., but finds that these cannot sufficiently explain the increase of temperature which is actually observed.

These older observations in mines also furnish fairly good data on the geothermal gradient, *i.e.*, the increase in depth corresponding to an increase of one degree of temperature. D'Aubŭisson (68) calculated values between 29.5 and 39.5 m. per degree Centigrade, von Trebra (1546) 31.3 m., Forbes (468) 27.5 to 33 m., Fox (475) 27.5 m., Moyle (1140*b*) 36.0 m. After a very careful compilation of measurements then known, Cordier (317) derived 25 m. per degree Centigrade, Reich (1281) compared the literature extensively and found 33.5 m. per degree Centigrade for Saxon mines. Erman (423) next calculated a temperature gradient of 23.5 m. per degree Centigrade from measurements in the boring at Rüdersdorf, Merian (1087) 31 m. per degree Centigrade in the boring at Pregny, near Genf, Walferdin (1575) 29.0 to 32.6 m. per degree Centigrade from various borings. Very detailed comparisons of data on the dependence of the earth's temperature upon depth, with discussion of all conditions which could influence these values, are found in Everett (438), Prestwich (1255), in the reports of Everett (439) to the British Association, in Günther's Handbuch der Geophysik (594, Vol. I, p. 335 *et seq.*), in the works of Koenigsberger (828), in Kayser's "Lehrbuch der Geologie" (802, Vol.

I, p. 57 *et seq.*), in Thiene (1525*a*), and others. Koenigsberger (842) finds that the normal gradient in horizontal strata is about 34 m. per degree Centigrade. Daly (327*a*) calculated the average gradient in Europe as 32 m. per degree Centigrade, in the United States as 42 m. per degree Centigrade.

All these investigations clearly show that in the crust of the earth the temperature decreases upward, corresponding to a heat flow into space. It is not yet clear whether the earth is slowly cooling or whether this cooling is compensated by heat production in the earth's interior, possibly by disintegration of radioactive substances. Since we are concerned with the distribution of heat in the outermost parts of the earth's crust, and its connection with geologic structure, it is of slight importance whether we reckon with inconceivably higher temperatures in the deeper crust, corresponding to the formation of the earth from a glowing mass (see, for instance, Moyle (1140*b*), Günther (594, p. 342)) or with relatively moderate temperatures of a few thousand degrees Centigrade, which of late have been assumed by Wiechert (802) as 3300°, Goldschmidt (569), 1100° to 1500°, Rösch (1299) and Linck (957) 5000°, Koenigsberger (826) 3000°, Mohorovicic (1129) 3000° to 4000°, and Gutenberg (611) even below 2000°.

So far as the distribution of heat in the earth's crust is determined by the current of heat which flows from the center towards the surface, it may be assumed that within each unit of surface area at right angles to the vertical the same amount of heat flows outward. Consequently, the geothermal gradient in the outer portions of the crust depends only upon the heat conductivity of the stratum in which it is measured, if the earth can be considered as composed of horizontal strata and if the superficial relief, soil characteristics, and temperature differences at the earth's surface can be disregarded. The theory of temperature distribution in the interior of the earth was first worked out by Fourier (474); later A. Thomson (1530, 1533, 1534), Hempel (699), Henrich (704, 705), Dunker (367), Boussinesq (221), and Jeffreys (762*b*) have considered this problem. Bischof (190) has tried to test these processes experimentally on the cooling of a glowing ball of basalt.

The Heat Conductivity of Rocks and Methods for Its Measurement.—λ denotes the amount of heat (in gram calories) which flows in unit time (1 sec.) through a cross-section of 1 sq. cm.,

if the temperature gradient at right angles to the cross-section is 1, *i.e.*, if the change of temperature is 1° C. in unit distance (1 cm.). The greatest heat conductivity is found in native silver, *i.e.*, $\lambda \sim 1$ gr. cal./cm. degree sec. In the rocks which compose the earth's crust, it is much smaller. Values for the heat conductivity of numerous rocks and kinds of soil are given by A. Jannettaz (762), Less (944), Weber (1589), Stadler (1467), Yamagawa (1653), Redenbacher (1277), Prestwich (1255), Friedländer (487), Koenigsberger (828), Mühlberg (842), Schulz (1404*a*), and others. Table XXI gives some average values (see also Landolt-Börnstein, "Physikalisch-chemische Tabellen," 5th edition (904)). The rocks were measured in a dry state. Moist granites, gneisses, etc., conduct about 10 per cent better; in other rocks the difference is greater, sometimes up to 100 per cent (see Prestwich (1255, p. 48 *et seq.*), Munthe (1149)). In schistose or stratified rock the conductivity is measured parallel to the schistosity or stratification.

TABLE XXI

Conductivity $\lambda \times 10^{-3}$					
Very fine sand	0.3	Sandy clay	2.2	Phyllite	5.9
Quartz sand	0.6	Clay	2.5	Sandstone	6.0
Coal	0.8	Andesite	3.1	Slate	6.1
Snow	1.1	Granite	4.0	Quartz	6.2
Water	1.4	Limestone	5.2	Rock salt	(6.6)?
Glass	2.1	Gneiss	5.4	Magnetite	30.0
		Porphyry	5.5		

Thus the heat conductivity of most rocks differs very little. Its influence on the geothermal gradient is therefore proportionately small. Recently Thornton (1535) gave a formula which connects the heat conductivity λ with the modulus of elasticity ϵ, the density ρ, and the velocity of sound $v = \sqrt{\epsilon/\rho}$. Then $\lambda \times 10^{-3} = v^2 \times \rho^2 \times 10^{-11}$, or likewise $\epsilon \times \rho \times 10^{-3}$. He also proved the correctness of this equation for a large number of substances.

The heat conductivity of rocks may be determined either absolutely or relative to the conductivity of known substances. Absolute measurements are very difficult. The extraordinarily great differences in the data of various authorities on heat conductivity of rocks may be due, however, to the variability of

rocks listed under the same name. Therefore relative comparisons of the rocks in one geologic area are of greater practical use, as Koenigsberger (828, 842) has emphasized on the basis of his exhaustive investigations in this special region.

Only a few especially suitable methods will be described from the numerous methods for determining the heat conductivity of solid substances. These and other methods may be found in all textbooks on experimental physics (for instance, Kohlrausch, "Handbuch der praktischen Physik" (851), Hobson and Diesselhorst (726)). Friedlander (487), according to Weber, immerses

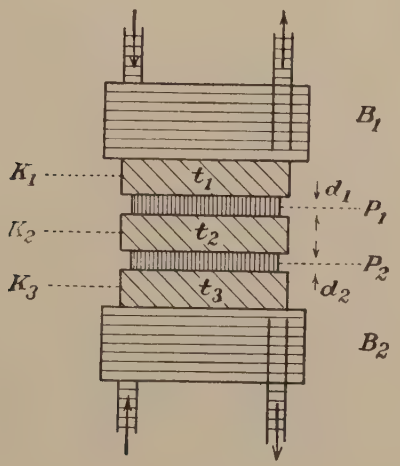


FIG. 81.

a uniformly heated cube in cold water and observes the cooling process by means of a thermoelement inserted in a fine hole drilled (for theoretical reasons) on a diagonal at one-third the distance from the center to the edge. Ingersoll and Koepp (765), as well as Henning (703), use similar methods. Niven (1182) and Melmer (1081) heat a cylinder of the material by a central wire and determine the temperature gradient against a constant exterior temperature.

Usually, however, the relative methods are to be preferred. Christiansen (305) lays two similar plates p_1 and p_2, of the material to be tested, with thicknesses d_1 and d_2, between three copper bars k_1, k_2, and k_3, whose temperatures t_1, t_2, and t_3, are determined by thermoelements (Fig. 81); k_1 and k_3 are tempered

by heating or cooling fluids in the vessels B_1 and B_2; k_3 may also be placed on a block of ice. In equilibrium,

$$\frac{\lambda_1}{\lambda_2} = \frac{d_1}{d_2} \times \frac{t_2 - t_3}{t_1 - t_2}.$$

Bäckström (86) and Berget (169) prevent loss of heat through radiation by a concentric outer mantel with temperature gradient as constant as possible (see also Jakob 760*a*).

The method of Voigt (1568), after de Senarmont (1430) is also well suited for comparative measurements. The known material and that to be investigated are placed together, on the diagonal or along a lateral median line, as a rectangular double plate. The upper surface of the double plate is coated with a mixture of elaidin acid and wax or with sodium sulphate. If the double plate is heated at a corner or truncated edge, the relative heat conductivities of the two substances composing the plates can be derived from the angle which the melting curves form at the boundary line between the plates.

In order to determine the heat conductivity parallel and at right angles to the cleavage in schistose rocks, a plate may be cut, as de Senarmont (1430) has shown for crystals, perpendicular to the cleavage. An electrically heated wire, or a silver tube through which a flame may be drawn, is inserted in the center. Melting ellipses are then formed on the elaidin acid-wax coating of the plate (see 842, pp. 142 *et seq.*). The proportion between their large and small axes gives the relation of the heat conductivity in the directions parallel and perpendicular to the cleavage. Such investigations have been carried out by Jannettaz (761), Badior (88), and others. Table XXII gives some average values for the relations of heat conductivity parallel and perpendicular to the stratification (cleavage) for various rocks.

The ratio is smaller in moist rocks than in dry ones, since the interstices in the strata are then filled with water. In a number

TABLE XXII

Kind of rock	Dry	Moist
Sandstone	1.03	
Limestone	1.06	
Calcareous phyllite	1.18	1.06 (1.12)
Gneiss	1.25	1.31 (1.37)
Slate	1.73	2.05 (2.36)

of cases in the table, this behavior is not clear because of the inhomogeneity of the material. Therefore values are given in brackets for dry rock from the same samples used for the data on moist rock.

It is easily recognized that, the more pronounced the stratification, the greater is the ratio between the two heat conductivities.

According to Weber (1589), Eucken (436), and Poole (1246), the heat conductivity increases with rising temperature in most materials. This factor cannot exert a very strong influence on temperature distribution in the earth's crust except in the already abnormal volcanic rock.

Influence of the Heat Conductivity of Rock Formations on the Geothermal Gradient.—Since the magnitude of the heat conductivity is dependent to a considerable extent upon the direction of the temperature gradient in the direction of rock stratification, the dip of the formations also has an influence on the geothermal gradient. The latter, measured parallel to the heat current, is proportional to the heat conductivity. Thus higher conductivity indicates a greater gradient. According to Koenigsberger (830; 842, p. 142), the geothermal gradient in stratified rocks, in the direction of gravity, actually varies with their dip. Thus in horizontal dry gneiss it is 28 to 29 m.; in phyllite in the same position 30 to 31 m.; in mica schist and dynamometamorphic slate 24 to 27 m.; in steeply inclined gneisses, schists, etc., over 35 to 37 m. In formations dipping less than 45°, the gradient is about 30 m. in dry gneiss, 32 m. in phyllite, 28 to 29 m. in mica schist. In moist rocks the gradient rises about 8 per cent with horizontal position, with dips of less than 45° about 5 per cent. Furthermore the dependence of the conductivity upon the direction of schistosity causes the heat current to diverge somewhat from the direction of greatest temperature gradient (*cf.* Voigt, "Kristallphysik," 1569, p. 377). This may be very conspicuous along marked unconformities in stratified rocks.

Influence of Surface Temperature on the Geothermal Gradient.—Because of climatic factors, the temperature at the earth's surface is subject to daily, annual, and irregular fluctuations, and is also dependent upon the geographic position of the observation point. The daily change of atmospheric temperature is noticeable to a depth of 2 to 3 m.; the annual, to 20 to 30 m. Accurate investigations on the penetration of atmospheric temperature

into the soil, which takes place with decreasing amplitudes and also phase retardation with depth, may be found in Thomson (1532) with exact formulae, Everett (438*a*), Dorn (354), Mischpeter (1121), Tamura (1514). The influence of the average annual temperature of the place of observation upon the temperature of the soil has been investigated by Singer (1451), Boussinesq (222), as well as Koenigsberger, Thoma, and Leier (844), who give an exhaustive discussion with special reference to the derivation of the average soil temperature as the starting point in the calculation of geothermal gradients, with numerous references to literature on soil temperatures. Kupffer (880) and Kämtz (799) tried to express the dependence of the average soil temperature upon geographic latitude (φ) as a function of $\sin^2 \varphi$. The dependence on the height above sea level is treated by Becquerel (152). According to Koenigsberger (842, p. 115), the average annual atmospheric temperature may be interpolated with sufficient accuracy from the average annual isotherms. These may be found in the meteorology volume of Berghaus' "Atlas" (Gotha), or in the "Meteorological Atlas" of the Geographical Society (London-Edinburgh). The elevation also must be taken into consideration. Here, according to Hann (638), 0.57° per 100 m. difference in height can be subtracted from the sea-level values given on the maps. The average temperature of the uppermost soil stratum in central European climates is usually a little higher (see Woeikow 1642, Schmidt 1391). This difference, depending upon the elevation of the observation point, may be taken from the following table after Koenigsberger and Mühlberg (842, p. 116):

Elevation...	0	500	1,000	1,500	2,000	2,500	(meters above base level)
Correction..	0.8	1.0	1.3	1.7	2.3	3.0°	(Centigrade)

In very dry climates (844), the difference is somewhat greater.

The condition of the earth's surface also influences the temperature of the soil. In forested areas the extreme values lie much closer together than in open fields, as the investigations of Schubert (1401), Müttrich (1150), and Ebermayer (373) have shown. Larger lakes or bodies of water lower the temperature of the uppermost strata for a distance of several kilometers (Supan (1502) and Koenigsberger (827; 842, p. 131)). The investigations of Henne (701) show a considerable influence of the character of the soil and rock on the thermal behavior of the

soil. According to Kerner von Marilaun (805), the direction of the heavens toward which the land faces is also important. Finally Woeikow (1641), von Toll (1544), and Büchler (266) point out the influence of snow covering and of ground ice. Leyst (950) and Woeikow (1642) treat exhaustively of the dependence of soil temperature upon meteorological factors. Schmidt (1374) gives a comprehensive account of the temperature distribution in the uppermost earth formations and draws conclusions as to the location of thermometer stations.

The Influence of Surface Relief on the Geothermal Gradient.— The decrease of the average soil temperature with height is about 0.57° per 100 m.; the aerothermal gradient is thus about 175 m. per degree Centigrade. The geothermal gradient, however, averages 30 to 35 m. per degree Centigrade. At a certain depth below the average surface of the earth within a large area, according to Günther (594, p. 340) probably at five kilometers, the geoisotherms, *i.e.*, surfaces of equal temperature, are no longer appreciably influenced by the surface configuration. In the space between this neutral surface and the irregular surface of the earth, the difference between the small geothermal gradient and the great aerothermal gradient must be compensated. Thus within mountains too large and in the adjacent valleys too small a geothermal gradient must be observed. This effect is very noticeable in the temperature of the rocks in long tunnels. Here the temperature (apart from various other influences) is lower than would correspond to the distance of the place in question from the earth's surface, assuming a gradient normal for level country. (According to Poggendorf (1244), Stapff (1470), Günther (594, p. 334), for geoisothermal surfaces in mountains the gradient should be measured perpendicularly to the isothermal surfaces, not in the plumb-line direction.) Pressel (1254) proposes a method of representing the form and position of isothermal surfaces under mountainous regions by models.

These facts have been confirmed in numerous large tunnels, and have been reported on in detail by Stapff (1470), (Gotthard); Koch (824), (Gotthard); Wagner (1572), (Arlberg); Fox (484), (Simplon); Koenigsberger (830, 842); (various Alpine tunnels); Niethammer (1165), (Simplon); Maurer (1063), (Jungfrau railway); Schardt (1351), (Simplon); Künzli (879), (Weissenstein tunnel). The works of Böhm (198), Prestwich (1255), and

Thoma (1528) are of a more general character, while Stapff (1471) is concerned with the influence of the rock temperatures on economic questions connected with tunnel construction in high mountains. Principles for the practical calculation of rock temperatures to be expected in tunnels with a given surface profile are given by Koenigsberger (842, p. 132 *et seq.*). The influence of the inclination of stratified rocks is also considered here. Thom (1527), investigates the corresponding relations for subterranean anticlines and folds. Water intrusion can greatly affect previously normal rock temperatures in tunnel construction, as Stapff (1470, 1473), Willmann (1630), Schardt (1352) have discussed.

The Measurement of Ground and Rock Temperatures.—In the measurement of soil temperatures at a few meters depth, or of temperatures in small borings in mining operations, normally only a short time is necessary for taking a reading—the time for erection of simple crating around the thermometer to prevent a change in the position of the thermometer during reading. The thermometer itself must not be too small (that is, it must have sufficient heat capacity). Graham (579) leaves a vessel of water in the drill hole for a considerable time, and measures its temperature periodically, in order to save thermometers. On the other hand, in order to keep the thermometer bulb always in place in the hole, when working in shallow holes a thermometer is used which has a very long tube connecting the bulb with the scale projecting from the hole (von Steeb (1474)). For continuous registration at slight depths, thermoelements or electric-resistance thermometers are most convenient (see Becquerel (152), Brückmann (255), Schmidt (1398*c*)). But for greater depths, in borings, etc., the long mobile cable conductions, according to Johnson and Adams (773), are so inconvenient that suitably constructed mercury thermometers are preferable.

For measurements in deep borings, ordinary thermometers also can be used if they are sufficiently covered with poorly conducting material to prevent a change of temperature while being hoisted upward. Generally, however, advantage is taken of the fact that rock temperatures in drill holes rise with increasing depth and that consequently the highest reading of the thermometer corresponds to the deepest point in the hole. For these readings, the thermometer must remain in the hole a sufficient length of time (usually 4 to 10 hr.). Before the lower-

ing of the thermometer, care must be taken that the atmospheric temperature of the thermometer is not too high. The thermometer may thus be constructed as a maximum thermometer, for which numerous serviceable models have been given. Koenigsberger (842) recommends maximum thermometers like many fever thermometers in which the uppermost 2 to 3 mm. of the mercury column are separated from the main portion by a small air bubble and thus remain in the highest position even if the mercury thread itself sinks again with falling temperatures. Apart from the possibility of displacing the separated end of the mercury, in hoisting, by jerks and bumps of the machinery to which the thermometer is fastened, Koenigsberger also notes the difficulty in transporting such thermometer and keeping the air bubble in the right position in the mercury column.

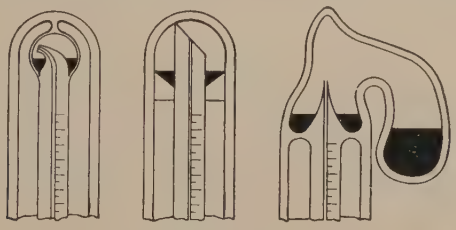


FIG. 82.

The overflow thermometers of Magnus (1029) and Walferdin (1574) are insensitive to vibrations. In these thermometers, as shown in Fig. 82, the upper end of the capillary is left open, cut off obliquely, or drawn out to a fine point, and surrounded by a storage vessel. By turning the thermometer upside down and cooling the bulb, enough mercury is sucked into the capillary to overflow into the storage vessel on heating the thermometer at the measuring point in the hole. On raising the thermometer, the mercury remaining in the capillary falls. The thermometer is then either brought to a known temperature in a bath and the distance of the thread from the top of the capillary read on a Centigrade scale, or it is slowly heated in a bath and the temperature determined at which the mercury in the capillary is just ready to overflow. Detailed descriptions of the construction and use of such overflow thermometers are found in Dunker (367, 368, 368*a*), and Henrich (706). Johnston and Adams (773) describe an overflow thermometer after Hallock (773) in which the amount of mercury separated is measured in a special capillary.

While the selection of the thermometer to be used depends more on the personal inclination of the observer, the accuracy and reliability of the measurements themselves depend largely upon the possibility of bringing the thermometer at the place of measurement to that unaltered temperature which is characteristic of the rock at the point in question. In the drilling of bore-holes, as well as in the construction and maintenance of mines, there are many influences which tend to obscure the true rock temperature. The heat of drilling or warm underground water may affect the rocks. Circulating water in the drill hole, whether from natural sources or from flushing the hole, produces serious changes in the rock temperature in the vicinity of the hole. Furthermore, these factors are active for a long time and this disturbance of natural conditions may penetrate far into the adjacent rocks. Special precautions should be observed, therefore, in order to measure the rock temperature as accurately as possible. Fox (475) has already noted these sources of error in temperature measurements in mines. Phillips (1234) gives directions for reliable measurements of this kind and proposes a scheme for them. In mines, therefore, the temperature measurements must be made in drill holes several meters deep with thermometers protected against circulating water and air.

In deep borings, it is more difficult to obtain satisfactory conditions for observation. With artesian water or oil, and gas under pressure, precise measurements in a well are often impossible; the only possible determination is the temperature of the flowing mass whose source is unknown. Thus the depth which actually corresponds to the measured temperature cannot be estimated. If gases develop in the well, cooling due to expansion of the gases may lower the temperature considerably. In dry wells the thermometer may be attached to a rope, a steel tape measure, or even to the drilling tools themselves if protected against damage from bumping. In wells filled with fluid, care must be taken to avoid circulation which conducts heat. For this purpose, plates of wood (Tanakadate, 1516), of leather (Koenigsberger, 842, p. 111), of rubber (Dunker 367), of rubber balls (Boussinesq, 221), or of clay balls (Dunker, 368) are installed, above and below the thermometer, to close the bore-hole and prevent circulation. They do not interfere with the movement of the thermometer. Dunker (368, 368*a*) shows that circulation is also absent if the hole is filled with very muddy

liquid. Köbrich (823) does not believe the influence of flushing circulation is very strong, yet it is questionable whether accidents may not have assisted in the comparison of temperatures with and without flushing. Steel pipes seem to have no appreciable influence, since their mass is extremely small in comparison with the surrounding rocks.

In most cases the thermometers are enclosed in a pressure-proof, water-tight envelope to avoid any elastic deformation of the thermometer by the hydrostatic pressure of the column of water. Such deformations result in too high temperature readings (up to several degrees) and even in collapsed and destroyed apparatus. A contrivance for inserting two to four thermometers in the drilling tools is given by Koenigsberger (842, p. 111). Von Orstrand (1204) also gives exhaustive consideration to the technique of temperature measurements in drill holes.

In order to secure an accuracy of 0.5°, the thermometer must remain at the place of measurement 3 to 10 hr., depending upon the manner of suspension, the character of the masses to be heated, the diameter of the borehole, the contents of the hole, and the accuracy desired. The most accurate temperatures are usually obtained at the bottom of the hole.

Without special importance for practical research, but of great importance for many questions of earth history, are methods of calculating temperatures which have prevailed during the formation of rock strata, or which these rocks must have attained in the course of time, as evidenced by the polymorphic or isomeric modification of crystals, *e.g.*, the change from α to β quartz at 575° or the changes in the series quartz-crystobalite-tridymite. Observations on the temperature factor in the chemical equilibria of various silicates and titanites, the dissociation of calcium carbonate, etc., have been published by Koenigsberger (829) and Mügge (1142).

Thermal Ground Investigation.—We may now consider those local influences which disturb the normal geothermal gradient. They may be divided into the following groups:

1. Deposits in the ground which, because of volcanic processes or because of their origin from such processes, possess a great amount of heat.

2. Disturbances of temperature through movement of substances within the crust of the earth, *e.g.*, ascending hot waters or gases.

3. Deposits which produce heat, *e.g.*, by chemical processes, radioactive changes, frictional heat, etc.

4. Deposits which produce anomalies in the geothermal gradient on account of their abnormal heat conductivity.

Molten masses which, by volcanic processes, approach or reach the surface of the earth and spread out as lava streams, carry great quantities of heat with them. The contact halos of the old granite stocks show the effect of such centers of heat upon rocks even several kilometers distant. If such volcanic action has taken place in recent times, the heat derived from depths in the earth will not yet be dissipated by conduction, but will still influence the geothermal gradient in the vicinity. Koenigsberger (832; 842, p. 138) has made investigations on the temperature relations near continually, or temporarily, active volcanoes. On the basis of his investigations, he gives (832) a time curve for decreasing volcanic activity with the composition of the vapors omitted (see also von Wolff (1642*c*, pp. 549–638)).

TABLE XXIII

Duration	Character of exhalation	Thermal gradient, meters per degree Centigrade
3 years	Alkaline and metallic chlorides	0.005
1–10 years	Ammonia and iron chlorides	0.01
50–1,000 years	Sulphur deposits	0.02–1.0
Up to 20,000 years	Hydrogen sulphide	1–10
50–500,000 years	Carbonic and boric acid over extensive areas	10–15

In the same paper Koenigsberger expresses the opinion that, by observation of the temperature at a depth of 30 m., an increase in volcanic activity may be predicted from a diminution of the geothermal gradient. According to Friedländer (487), the gradient in volcanic regions is further diminished by the poor conductivity of volcanic rocks.

Thus volcanic processes continue to affect the geothermal gradient for a long time. Daubrée (330) has already called attention to the connection between recent volcanic activity and the small gradient in the bore-hole at Neuffen as reported by Mandelslohe (1042). Branco (234) brought these observations into agreement with the general volcanic structure of the

region. Schmidt (1394), as well as Braun and Waitz (239), has found similar relations in the region of the young volcanic basalts at Sulz on the Neckar. By comparison of the measurements of temperature increase in the bore-hole at Neuffen with those in the oil regions in Alsace, Branco (235) shows that in every case the most careful consideration must be taken of the special geological structure of the area.

The anomalies of soil temperature at Budapest, described by Szabo (1505), Zsigmondy (1670*a*), and Zoeppritz (1666), may be caused by still older volcanic events, although indirectly by hot springs due to these volcanics. Becker (144) and Locke (976) have thoroughly investigated the high rock temperatures of the large rich ore deposits in the Comstock lode, in the Forman shaft at Virginia City. Stapff (1472) also discusses these. Besides the explanation of high rock temperatures as the effect of a volcanic center in the deeper subsoil aided by rising water, a further source of heat can be found in the kaolinization of the trachytic country rock.

This last example leads to the second group of disturbances of normal rock temperatures, *i.e.*, subterranean circulating waters. These may either come from greater depths, or may be heated by volcanic processes, and cause supernormal heating of the rocks through which they flow; or they may originate in higher formations, and cool the rocks in the vicinity of their subterranean course. Bischoff (191) has already noted that the high temperatures of many springs are caused by their origin in deeper warmer formations of the earth's crust. Willmann (1630) discusses the influence of ground water on the temperature of tunnels. Recent detailed investigations on the hot springs in California have been published by Waring (1578), Bryan (264), Day (335), Day and Allen (336); Wright (1647) has made similar investigations in Iceland.

A systematic measurement of the temperature of all springs in a larger area is often of special importance for the purposes of practical geology. Karrer (800) has made such a survey of the area traversed by the Franz Joseph Aqueduct of the city of Vienna. The temperature of the springs may often give a clue to their origin, as found by Mezger (1101). A very careful measurement of the soil temperatures in the thermal region of Stubicke Toplice, in Croatia, made by Steeb and his collaborators (572, 1474) at a depth of 0.5 to 1 m., is the basis for the con-

struction of lines of equal soil temperature for this depth (Fig. 83). Figure 84 shows the vertical distribution of temperature along the line *A-G* of Fig. 83. The consideration of atmospheric temperature has been discussed in detail. The soil isotherms show clearly the individual hot springs and their mutual geologic and hydrographic relations. Measurements of this kind, espe-

FIG. 83.

cially if extended to still greater depths, could furnish valuable information on the subterranean distribution of watercourses in many of the thermal regions. In active volcanic regions, as for instance in Italy, where terrestrial heat is to be used for generating power, such measurements may serve to locate the most favorable points for drilling. These points with the smallest geothermal gradient may be found with small cost by systematic measurements of the soil temperature in shallow bore-holes.

The most important process in the interior of the earth, by which heat is liberated, is the decomposition of radioactive

substances. This has already been discussed at length on p. 107 *et seq.* The investigations and calculations of Himstedt (723), Liebenow (955), Koenigsberger (826), von Wolff (1642*b*), Joly (775 784*b*), Lotz, (980*a*), Elster and Geitel (389), Becker (145), and others, have shown that with a concentration of radioactive substances in the whole earth similar to that in the uppermost formations, the earth is growing hotter instead of cooler. According to Strutt (1495) the radioactive materials seem to be confined preeminently to the rock mantle of the earth (see also Cotter (320*a*) and Adams (9*a*)). Yet even in the most strongly active regions the quantity of these heat-producing radioactive materials is so small that noticeable local heating and influence on the geothermal gradient are not to be expected (see Lees (929)). Even

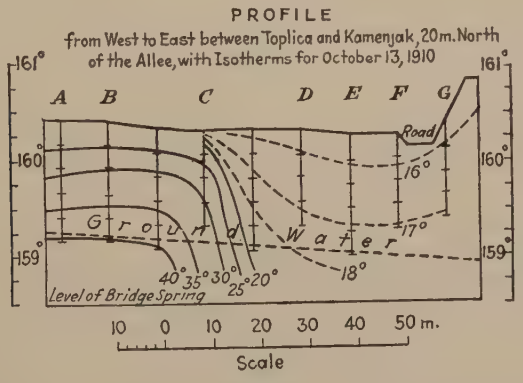


FIG. 84.

in the uranium mines of St. Joachim Valley, the geothermal gradient appears to be normal (see Mache and Schweidler (1015)).

Heat may also be generated in the earth's crust by internal chemical reactions in coal deposits. In the Konsolidation coal mine, near Gelsenkirchen, for instance, the temperature in the coal seam was found to be a degree higher than in the surrounding rock (171). Even during the incipient carbonization of organic substances in marine deposits, notable quantities of heat can be liberated, as the observations of Petersen (1223) show. On the Danish coast, with a water temperature of $-0.1°$, he found a temperature of $+7°$ at 1 m. depth in the mud. The decrease of the geothermal gradient above coal deposits has often been observed. Below the coal mines, it rises correspondingly above the normal value and may even become negative. Reference

may be made to the works of Matteuci (1056) on Monte Massi, in Tuscany; Leprince-Ringuet (942*a*), Prestwich (1255), Jones (788), and Rees (1278*a*) on English coal mines; Kolb (852), Willert (1628) on Austrian; as well as publications of Koenigsberger. Thus, in geologically suitable cases, the proximity of a coal seam can be detected from the values of the geothermal gradient found in the boring. The experiences of Van Wervecke (1602) in the coal borings at Buix show the necessity of careful testing of all circumstances which could bring about a diminution of the geothermal gradient in the region under examination. With reference to coal mines, it should especially be noted that oxidation of coal in surface outcrops may cause additional heating and that the liberation of gases and ventilation may cause cooling. The thermometer must therefore be inserted in drill holes to a depth where these disturbances are no longer effective.

Of the high temperatures in salt mines we shall speak more in detail later. Koenigsberger (836) emphasizes the fact that heat may develop from the hydration of anhydrite into gypsum. The strong development of heat in many oil deposits is very marked. This may be due to chemical reactions in the oil, especially oxidation and polymerization (see Stremme (1493)). Consequently a notable decrease in geothermal gradient is very often found over large oil fields. Daubrée (331) observed this phenomenon in Alsace; Thomson (1529) in the oilfields of Baku; Arctowski (57) in the Polish oilfields; Van Orstrand (1204*a*) in California and Wyoming; Höfer (728), Lindgren (958), Pascoe (1211), White, (1605) refer repeatedly to the fact; DeGolyer (343*a*) finds the same true for Mexico. Zuber (1671) and Koenigsberger (839*e*, 842) consider systematic temperature measurements during the drilling of an oil well as extremely important, and give directions for the execution of such investigations. These are undoubtedly apt to give important hints on the prospects of the well and are very inexpensive. Because of the lowering of the geothermal gradient which it causes, Werner (1601*a*) suggests the detection of oil in the deeper formations by temperature measurements in shallow borings. The various disturbing causes which influence the geothermal gradient are too numerous and much too small for such measurements to be sufficiently accurate and safe for practical purposes.

In many cases, chemical reactions in ore deposits, *e.g.*, the oxidation of pyrite (which often acts with the same thermal

tendency as an accessory in other deposits), can cause a local development of heat and thus influence the geothermal gradient. D'Aubuisson (69) calls attention to this source of heat. The spontaneous earth currents mentioned on p. 155 *et seq.* also indicate the same kind of chemical changes in the vicinity of many such ore deposits. According to Koenigsberger (827), even very slight amounts of heat, if generated continually, are sufficient to cause rather strong disturbances of the normal geothermal gradient. With friction of blocks in tectonic movements, the time is too short to produce sufficient heat to raise the local temperature appreciably. It is still uncertain whether this view is contradicted by the investigations of Jones (789), Darton (328), Stainier (1469), Briggs, Owen and Wilson (245*a*), on the connection between mine temperatures and geologic disturbances.

The heat conductivity of rocks in dependence upon the schistosity or bedding and water conditions has been considered by Koenigsberger (828; 842, p. 135 *et seq.*) in reporting on the temperatures found in various tunnels. It is not certain whether the differences between slate and granite which Henwood (707) found in the mines of Cornwall, are due to the same cause. The high conductivity of many ores cannot be manifested practically in changes of the geothermal gradient except in very large and thick deposits. No instances of such an effect on the geothermal gradient are known at present. A very important role, however, is played by the high conductivity of salt ($k = 0.007$, according to Sollas (1463) even 0.011) in the origin of the high temperatures of many salt mines. Huyssen (756), Sollas (1463), Albrecht (16), Busch (279), Koenigsberger (836), have all treated this question. In this connection, it must be considered that rock salt, which often crystallizes very purely, is very permeable to heat radiation, and that the entire flow of heat may be materially intensified by radiation through thick salt deposits. This may be much stronger than laboratory measurements would suggest. This effect may be increased still further by the heat of hydration in anhydrite and oxidation processes in adjacent oil deposits. On the other hand, the opinion that this heat is the residue of that liberated during the upward movement of the salt domes, by compression and internal friction or by chemical reactions, can hardly be correct, since that possible increase in temperature must have been dissipated long ago. The high temperatures of

many salt deposits, and the corresponding large geothermal gradient in the overlying formations, may occasionally be of use in detecting the approach to a salt dome. In establishing the position and extent of salt domes, however, there are so many geophysical methods, such as the seismic, gravitational, electric, and magnetic methods, which have been tested and proved, that deep borings and temperature measurements need hardly be considered.

ABBREVIATIONS USED IN THE BIBLIOGRAPHY

AAL	Abhandlungen d. math.-phys. Classe der kgl. Gesellschaft der Wissenschaften, Leipzig.
AB	Abhandlungen der kgl. Akademie der Wissenschaften zu Berlin, Berlin (physikal.-math. Kl.).
ABelg	Annales des mines de Belgique, Bruxelles.
ABM	Annales du Bureau Central Météorologique de France, I. Mémoires, Paris.
ABr	Annales de la Société Scientifique de Bruxelles. Bruxelles Paris —Louvain.
ACh	Annales de Chimie et de Physique, Paris.
AF	Abderhaldens Fortschritte der naturwissenschaftlichen Forschung, Berlin Wien.
AFr	Annales des Mines de France, Paris.
AG	Archives des Sciences Physiques et Naturelles, Genève.
AGA	Abhandlungen der kgl. Gesellschaft der Wissenschaften und der Georg-Augusts-Universität zu Göttingen (Math.-Physik), Göttingen.
AGW	Abhandlungen der k. u. k. Geologischen Reichsanstalt, Wien.
AH	Annalen der Hydrographie und maritimen Meteorologie, Berlin.
AJ	The American Journal of Science (Silliman Journal), New Haven, Conn.
AL	Arbeiten des Aeronautischen Instituts in Lindenberg, Berlin.
AM	Abhandlungen der kgl. bayerischen Akademie der Wissenschaften, math.-naturw. Abteilung, München.
AMé	Annuaire de la Société météorologique de France, Paris.
AMP	Archiv der Mathematik und Physik, Leipzig—Berlin.
Amp	Arkiv fór Matematik, Astronomi och Fysik, Stockholm.
AN	Astronomische Nachrichten, Kiel.
AÖCh	Allgemeine österreichische Chemiker- und Techniker-Zeitung, Wien.
AP	Annalen der Physik, Serie 1–4, Leipzig.
APG	Annales de l'Institut de Physique du Globe, Paris.
AphJ	Astrophysical Journal, Chicago and New York.
AR	Annali dell' Ufficio centrale meteorologico e geodynamico italiano, Roma.
AsJ	Astronomical Journal, Albany.
AT	Annales Télégraphiques, Paris.
AV	Allgemeine Vermessungsnachrichten, Liebenwerda.
BA	Beiträge zur Physik der freien Atmosphäre, Leipzig.
BAA	Bulletin des travaux de la classe des sciences math. et natur. de l'Académie d. Sci. et d. Arts d. Slaves du Sud de Zagreb.

BAC Bulletin international de l'Académie des sciences de Cracovie (Anzeiger der Akad. d. Wiss. in Krakau), Cracovie.
BAP Bulletin de l'Académie Impériale des Sciences de St. Pétersbourg.
BB Sitzungsberichte der kgl. preussischen Akademie der Wissenschaften, Berlin.
Bb Der Bergbau, Gelsenkirchen.
BEJ Bulletin of the Imp. Earthquake Investigation Committee, Tokyo.
BF Berichte der naturforschenden Gesellschaft zu Freiburg i. Br., Freiburg i. Br.
BG Gerland's Beiträge zur Geophysik.
BGA Bulletin of the Geological Society of America, Rochester, N.Y.
BGF Bulletin de la Société géologique de France, Paris.
BGR Bulletins du Comité géologique, St. Pétersbourg.
BH Berg- und Hüttenmännische Zeitung, Nordhausen u. Leipzig.
BHJ Berg- und Hüttenmännisches Jahrbuch, Leoben; Wien—Berlin.
BJ Der Bauingenieur, Zeitschrift für das gesamte Bauwesen, Berlin.
BJP Bulletin of the Institute of practical geophysics of the Supreme Council of public economy, Leningrad.
BNL Bulletin de la Société Impérial des Naturalistes "Kosmos," Lwow.
BNM Bulletin de la Société Imp. des naturalistes de Moscou, Moscou.
BR Reports of the Meeting of the British Association for the Advancement of Science, London.
BRC Bulletin of the National Research Council, Washington.
BS Bulletin of the Seismological Society of America, Stanford University (Calif.).
BSA Berichte der Internationalen seismologischen Assoziation.
BSG Berichte der Deutschen seismologischen Gesellschaft, Jena.
BSJ Bollettino della Società seismologica italiana, Roma (Modena).
BU Supplément à la Bibliothèque Universelle et Revue Suisse Archives des Sciences Physiques et Naturelles, Genève.
Bu Braunkohlen- und Brikett-Industrie, Halle a. S.

CG Colliery Guardian, London.
Ch The Chemist, London.
CJ Canadian Mining Journal, Toronto.
CR Comptes Rendus hebdomaires des séances de l'académie des sciences, Paris.
CRB Comptes Rendus du Congrès International de Radiologie et d'Electricité, Bruxelles 1911.
CRS Comptes Rendus des séances de la Commission Sismique Permanente, St. Pétersbourg.
CS U. S. Coast and Geodetic Survey, Washington.
CT Ciel et Terre, Bruxelles.

DP Dingler's Polytechnisches Journal, Berlin.
DRP Deutsches Reichspatent (Anmeldedatum); † = verfallen.
DW Denkschriften der k. u. k. Akademie der Wissenschaften, math.-naturw. Kl., Wien.

EbW Erdbebenwarte; Neueste Erdbebennachrichten, Laibach.
EC Erdmann's Journal für praktische Chemie, Leipzig.
EE Edelerden und Erze, München.
EEl Eclairage Electrique, Paris.
EG Economic Geology, Lancaster, Pa.
EH Eclogae geologicae Helvetiae, Lausanne.
El The Electrician, London.
EM Encyklopädie der mathematischen Wissenschaften mit Einschluss ihrer Anwendungen, Leipzig.
EN Elektrische Nachrichten-Technik, Berlin.
Engg Engineering and Mining Journal, New York.
ETZ Elektrotechnische Zeitschrift, Berlin.
EW Electrical World and Engineer, New York.
EY The Edinburgh New Philosophical Journal, Edinburgh.

FA Forschungen auf dem Gebiete der Agrikultur-Physik, Heidelberg.
Fe Fennia, Bulletin de la Société de géographie de Finlande, Helsingfors.
Fo Forschungen zur deutschen Landes und Volkskunde, Stuttgart.

GA Geologisches Archiv, Königsberg.
GC Génie Civil. Révue générale hebdomaire des industries françaises et étrangères, Paris.
Ge Der Geologe, Leipzig.
GeA Geografiske Annaler, Kristiania.
GJ Geographical Journal, including the proceedings of the Roy. Geographical Society, London.
GJM Geognostische Jahreshefte, München.
Gl Glückauf; Berg- und Hüttenmännische Zeitschrift, Essen.
GM Geological Magazine, London.
GN Nachrichten von der kgl. Gesellschaft der Wissenschaften zu Göttingen, Berlin.
GnF Sitzungsberichte der Gesellschaft Naturforschender Freunde zu Berlin, Berlin.
Go Gornij Journal, Moskau.
GP Proceedings of the Geological Society of London, London.
GR Geologische Rundschau, Berlin.
GS Memoirs of the Geological Survey, England and Wales, London.

HB Berichte über die Mitteilungen von Freunden der Naturwissenschaften in Wien, Wien.
HE Himmel und Erde, Leipzig und Berlin.
He Helios, Fach- u. Export-Zeitschrift für Elektrotechnik, Leipzig.
HP Handbuch der Physik, herausgegeben von H. Geiger und K. Scheel, Berlin.

IGU Bulletin of the International Geodetic and Geophysical Union. Section of Magnetism and Electricity.
IZBE Internationale Zeitschrift für Bohrtechnik, Erdölbergbau und Geologie, Wien.

JA Jernkontorets Annaler, Stockholm.
JB Internationale Bergwirtschaft, Leipzig.
Jb Iberica, Madrid.
JC Journal of the Royal Astronomical Society of Canada, Toronto.
JCT Iron and Coal Trades Review, London.
JFr Journal of the Franklin Institute, Philadelphia.
JG Journal of Geology, Chicago.
JGB Jahrbuch der preussischen geologischen Landesanstalt, Berlin.
JGW Jahrbuch der k. u. k. geologischen Reichs-(Bundes-) Anstalt, Wien.
JH Jahrbuch des Halle'schen Verbandes zur Erforschung der mitteldeutschen Bodenschätze und ihrer Verwertung, Halle a. S.
JJA Japanese Journal of Astronomy and Geophysics, Transactions and Abstracts, Tokyo.
JM Journal des Mines, Paris.
Jn L'Institut, Journal des Académies et Sociétés Scientifiques de la France et de l'Etranger, Paris.
JO Journal of the Optical Society of America and Review of Scientific Instruments, Ithaca, N. Y.
JOG Jahresberichte und Mitteilungen des Oberrheinischen Geologischen Vereins, Stuttgart. Neue Folge.
Jph Journal de Physique (et le Radium), Paris.
JR Jahrbuch für Radioaktivität und Elektronik, Leipzig.
JS Jahrbuch für das Berg- und Hüttenwesen in Sachsen, Freiberg.
JSch Jahresberichte der Schlesischen Gesellschaft für Vaterländische Kultur, Breslau.
JSE Jahresberichte des schweizerischen Erdbebendienstes, Zürich.
JSJ Journal of Scientific Instruments, London.
JST Journal of the Society of Telegraph-Engineers and Electricians, London—New York.
JT Jahrbuch der drahtlosen Telegraphie und Telephonie (Zeitschrift für Hochfrequenztechnik), Berlin.
JW Jahreshefte des Vereins für vaterländische Naturkunde in Württemberg, Stuttgart.
JWA Journal of the Washington Academy of Sciences, Baltimore.
JZ Jahresbericht der physikalischen Gesellschaft in Zürich, Uster-Zürich.

Ka Kali, Halle a. S.
KB Tidskrift for Kemi og Bergveesen, Kristiania.

LB Berichte über die Verhandlungen der kgl. Sächsischen Akademie der Wissenschaften, Leipzig.
LE La Lumière Electrique, Paris.

MB Sitzungsberichte der math.-phys. Kl. der kgl. Bayerischen Akademie der Wissenschaften, München.
ME Metall und Erz, Zeitschrift f. Metallhüttenwesen u. Bergbau, Halle a. S.
MF Mémoires présentés par divers savants à l'Académie . . . de France, Paris.

MG Monographs of the U. S. Geological Survey, Washington.
MgM Mining Magazine, London.
MJ Mining Journal, London.
MiM Mining and Metallurgy, New York.
ML Mitteilungen des Aeronautischen Observatoriums in Lindenberg, Berlin.
MM Mitteilungen aus dem Markscheidewesen, Freiberg i. Sa.
MMB Kgl. Magnetisch en Meteorologisch Observatorium te Batavia, Verhandelingen, Batavia.
MML Mitteilungen aus der Grossherzogl. Mecklenburgischen Geologischen Landesanstalt, Rostock.
MN Monthly Notices of the Royal Astronomical Society, London.
MNGS Monthly Notices of the Royal Society, Geophysical Supplement, London.
MP Mémoires de l'Académie Imp. des Sciences de St. Pétersbourg, St. Pétersbourg.
MPG Mitteilungen der Philomatischen Gesellschaft in Strassburg, Strassburg.
MR Montanistische Rundschau, Wien—Berlin.
MS Mitteilungen des Zentralbüros der intern. seismologischen Association, Leipzig. (In Gerland's Beiträgen.)
MT Mémoires de l'Académie des sciences inscriptions et belles lettres de Toulouse, Toulouse.
MW Mitteilungen der Erdbebenkommission der k. u. k. Akad. d. Wiss., Wien.
MWR Monthly Weather Review, Washington.
MZ Meterologische Zeitschrift, Braunschweig.

Na Die Naturwissenschaften, Berlin.
NaR Rendeconti della R. Accademia delle science fisiche e matematiche, Napoli.
NC Il Nuove Cimento, Bologna.
NL Nature, London.
NM Neues Jahrbuch für Mineralogie, Geologie und Paläontologie, Stuttgart.
NP Nature, Paris.
NR Naturwissenschaftliche Rundschau, Berlin.
NW Naturwissenschaftl. Wochenschrift, Jena.

ÖB Österreichische Monatsschrift für den öffentlichen Baudienst und das Berg- und Hüttenwesen, Wien.
ObL Observatory, London.
OE Onde Electrique, Paris.
OfvH Öfversigt Finska Vetenskaps-Societetens Förhandlingar. A. Mat. och Naturw., Helsingfors.
OfvS Oversigt of Kgl. Vetenskaps-Academiens Förhandlingar, Stockholm.
ÖV Oesterreichische Zeitschrift für Vermessungswesen, Wien.

Pc	Petroleum, Zeitschrift f. d. ges. Interessen der Mineralölindustrie etc., Berlin—Wien.
PEJ	Publications of the Earthquake Investigation Committee in foreign languages, Tokyo.
PG	A. Petermanns Geographische Mitteilungen, Gotha.
PM	The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science, London.
PO	Publications of the Dominion Observatory, Ottawa.
PR	The Physical Review. A Journal of experimental and theoretical physics, Menasha, Wis.
Pr	Prometheus, Leipzig.
PrA	Proceedings of the American Philosophical Society held at Philadelphia for promoting useful knowledge, Philadelphia.
PrC	Proceedings of the Cambridge Philosophical Society, Cambridge (England).
PrE	Proceedings of the Royal Society of Edinburgh, Edinburgh and London.
PrJ	Proceedings of the R. Irish Academy, Dublin.
PrL	Proceedings of the London Mathematical Society, London.
PrP	The Physical Society of London, Proceedings.
PrR	Proceedings of the Institute of Radio Engineers, New York.
PrS	Proceedings of the Royal Society, Serie A, Mathem. and Phys. Sciences, London.
PrSW	Proceedings of the South Wales Institute of Engineers, Cardiff.
PrT	Proceedings of the Tôkyô Mathematico-physical Society, Tokyo.
PrW	Proceeding of the National Academy of Sciences of the U.S.A., Washington.
PrWA	Proceedings der koninkl. Akademie van Wetenschappen te Amsterdam.
PT	Philosophical Transactions of the Royal Society of London (A), London.
PZ	Physikalische Zeitschrift, Leipzig.
QJ	Quarterly Journal of the Geolog. Soc. London 1904 (Ref. in NL 1904, S. 111).
RA	Revista de la R. Academia de ciencias exactas, físicas y naturales de Madrid, Madrid.
Ra	Radium, Paris.
RE	Repertorium der Physik, Berlin.
RF	Rivista di fisica, matematica e scienze naturali, Pavia.
RG	Revue générale des sciences pures et appliquées, Paris.
RL	Atti della Reale accademia dei Lincei, Rendeconti Classe di sc. fis., math. e nat., Roma.
RM	Repertorium f. Meteorologie (Wild), St. Petersburg.
Rm	Revue météorologique, Odessa.
RMM	Revue universelle des mines de la métallurgie, des travaux publics, des sciences et des arts, appliqués à l'industrie, Paris.

RP	Rapports présentés au Congrès international de Physique 1900 à Paris.
RS	Revue Scientifique, Paris.
SAD	Scientific Proceedings of the Roy. Astronomical Society of Dublin, Dublin.
SAH	Kungl. Svenska Vetenskapsakademiens Handlingar, Stockholm.
Sc	Science, New York.
SD	The Scientific Proceedings of the Royal Dublin Society.
SE	Stahl und Eisen, Zeitschrift für das deutsche Hüttenwesen, Düsseldorf.
SEZ	Schweizerische Elektrotechnische Zeitschrift, Zürich.
SJ	Journal für Chemie und Physik. Herausgeg. v. J. S. C. Schweigger, Nürnberg.
SJJ	Seismological Journal of Japan, Yokohama.
SK	Schriften der physikalisch-ökonomischen Gesellschaft zu Königsberg i. Pr.
SS	Scientific papers of the Bureau of Standards, Washington.
StA	Annals of Electricity, Magnetism and Chemistry (by W. Sturgeon), London.
Ste	Steinbruch u. Sandgrube, Halle a. S.
Str	Strahlentherapie, Berlin—Wien.
Ta	Annals of Philosophy, or Magazine of Chemistry, Mineralogy, Mechanics and the Arts (by T. Thomson), London.
TB	Technische Blätter (Wochenschrift zur Deutschen Bergwerkszeitung), Essen.
TF	Telegraphen- und Fernsprechtechnik, Berlin.
TGM	Talleres del instituto geográfico, Madrid.
TM	Terrestrial Magnetism and Atmospherical Electricity, Baltimore.
TN	Tijdskrift d. Nederlands Radioenginers, Amsterdam.
TR	Records of General Science (by Rd. & Thos. Thomson), London.
TrA	Transactions of the American Philosophical Society, Philadelphia.
TrC	Transactions of the Royal Geological Society of Cornwall, Penzance.
TrCP	Reports and Transactions of the Royal Polytechnic Society of Cornwall, Falmouth.
TrE	Transactions of the American Electrotechnical Society, Philadelphia.
TrEd	Transactions of the Royal Society of Edinburgh.
TrG	Transactions of the American Geophysical Union, Washington.
TrM	Transactions of the American Institute of Mining and Metallurgical Engineers, New York.
TrP	Transactions of the Cambridge Philosophical Society, Cambridge.
TrR	Proceedings and Transactions of the Royal Society of Canada, Montreal, Ottawa.
TrS	Transactions of the Royal Irish Academy, Dublin.
TrSJ	Transactions of the Seismological Society of Japan, Yokohama.
TT	Teknisk Tidskrift, Stockholm.

Um Umschau, Frankfurt a. M.

VDP Verhandlungen der Deutschen Physikalischen Gesellschaft, Braunschweig.
VE Verhandlungen der . . . allgemeinen Konferenz der Internationalen Erdmessung.
VG Veröffentlichungen des Kgl. Preuss. Geodätischen Instituts, Neue Folge.
VGW Verhandlungen der k. u. k. geologischen Reichs-(Bundes-)Anstalt, Wien.
VH Verhandelingen van het geologisch en mijnbowkundige Genootschap voor Nederland en Koloniën, Geologische Serie, s'Gravenhage.
VJ Veröffentlichungen der Reichszentrale für Erdbebenforschung in Jena.
VK Skrifter utgit av Videnskapsselskapet i Kristiania, I. Mat.-Nat. Kl., Kristiania.
VM Veröffentlichungen des Kgl. Preuss. meteorologischen Instituts, Berlin.
VP Verhandlungen der physikalischen Gesellschaft, Berlin.
VR Verhandlungen des Naturhistorischen Vereins der preussischen Rheinlande und Westfalens, Bonn.
VS Verhandlungen der . . . internationalen Seismologischen Konferenz.
VSt Veröffentlichungen des Zentralbüros der Internationalen seismologischen Assoziation.
VZ Vierteljahrsschrift der naturforschenden Gesellschaft in Zürich, Zürich.
VZE Veröffentlichungen des Zentralbüros der internationalen Erdmessung, Berlin, Neue Folge.

WA Anzeiger der k. u. k. Akademie der Wissenschaften, Wien.
WB Sitzungsberichte der k. u. k. Akademie der Wissenschaften, Wien.
WE The Electrical Magazine (by V. Walker), London and Paris.
We Wetter, Berlin.
Wl Weltall, Berlin.
WR Wissenschaftliche Abhandlungen der physikalisch-technischen Reichsanstalt, Berlin.
WYG Proceedings of the Geological and Polytechnic Society of the West Riding of Yorkshire, Leeds.

ZaC Zeitschrift für angewandte Chemie, Leipzig.
ZaG Zeitschrift für angewandte Geophysik, Berlin.
ZaMP Zeitschrift für angewandte Mathematik und Mechanik, Berlin.
ZB Zeitschrift für Balneologie, Klimatologie und Kurorthygiene, Berlin.
ZBB Zeitschrift des intern. Vereins der Bohringenieure und Bohrtechniker, Wien.
ZBS Zeitschrift f. d. Berg-, Hütten- und Salinenwesen im preuss. Staate, Berlin.

ZC	Zeitschrift für anorganische und allgemeine Chemie, Leipzig.
ZDG	Zeitschrift der Deutschen geologischen Gesellschaft, Stuttgart.
ZE	Zeitschrift für Elektrochemie und angewandte physikalische Chemie, Leipzig.
ZF	Zeitschrift für Feinmechanik, Berlin-Nicolassee.
ZFP	Zeitschrift für Feinmechanik und Präzision, Erfurt.
ZFT	Zeitschrift für Fernmeldetechnik, Werk- und Gerätebau, München —Berlin.
ZG	Zeitschrift für Geophysik, Braunschweig.
ZGE	Zeitschrift der Gesellschaft für Erdkunde zu Berlin, Berlin.
ZJ	Zeitschrift für Instrumentenkunde, Berlin.
ZK	Zeitschrift für Kristallographie, Leipzig.
ZM	Zentralblatt für Mineralogie, Geologie und Paläontologie, Stuttgart.
ZMP	Zeitschrift für Mathematik und Physik, Leipzig.
ZO	Zeitschrift des Oberschl. Berg- und Hüttenmännischen Vereins. Kattowitz.
ZP	Zeitschrift für Physik, Braunschweig—Berlin.
ZpG	Zeitschrift für praktische Geologie, Halle a. S.
ZtP	Zeitschrift für technische Physik, Leipzig.
ZV	Zeitschrift für Vermessungswesen, Stuttgart.
ZVJ	Zeitschrift des Vereins deutscher Ingenieure, Berlin.
ZWG	Zeitschrift für wissenschaftliche Geographie, Wien.

BIBLIOGRAPHY[1]

1. Abbe, Cl. TM **3,** 135/6, 1898. *68.*
1*a*. Abbot, C. G. NL **116,** 785, 1925. *67.*
2. Abbot, H. L. AJ **15,** 178/84, 1878. *246.*
3. Abels, R. TM **27,** 119/20, 1922. *67.*
4. Abraham, M. JT **18,** 322/37, 1921; **19,** 252/4, 1922. *200.*
5. ———; Traubenberg, H. Rausch v., Pusch. PZ **20,** 145/7, 1919. *141.*
5*a*. Absalom, H. W. L. TM **32,** 1/4, 1927. *67.*
6. Abt, A. AP 3 **68,** 658/73, 1899. *90.*
7. Ackley, Walter T., Ralph, Clifton M. JFr **198,** 834/5, 1924; CG **129,** 89, 1925. *240.*

Adami, F., Günther, S., s. (595).

8. Adams, F. JG **20,** 87/118, 1912; Ka **15,** 152, 1921. *36, 207.*
8*a*. ———; Cooker, Ernest G. AJ 4 **22,** 95/123, 1906; Publ. Carnegie-Inst. Wash. 46, 1906 (69 pp.). *207.*

——— Fr. D.; Eve, A. S., s. (436a).

9. ———, Leason, H.; Williamson, Erskine, D. JFr **195,** 475/529, 1923. Johnston, Journ. Amer. Chem. Soc. **41,** 12/42, 1919. *36.*

——— L. H., Johnston, John, s. (773).

9*a*. ——— L. A. JWA **14,** 459, 1924. *281.*
10. Agamemnone, G. Estratto dal Boll. della Soc. Sism. Ital. 8, Modena 1903 (22 S.); Ref. TM. **9,** 97/8, 1905. *95, 96, 97, 234.*
11. Aigner, F. Unterwasserschalltechnik. Berlin 1922 (322 pp.). *241.*

Airy, G. B.

12. PT **145,** 101/4, 1855. *37.*
13. PT **152,** 273/88, 1862. *148.*
14. AG **33,** 129/35, 1868; PT **158,** 465/72, 1868. *154.*
15. PT **160,** 215/26, 1870; PrS **18,** 184/5, 1870. *154.*

16. Albrecht, D. Ka **16,** 413, 1922. *283.*
17. Aldrich. EG **18,** 562/74, 1923. *104.*
18. Alenius, C. A. Fe **22,** No. 6, 1904/5. (18 pp.). *100.*
19. Alessio, A. GJ **63,** 33/45, 1924. *38.*

Allan, G. E.

20. PM 6 **7,** 45/61, 1904. *96.*
21. PM 6 **17,** 572/81, 1909. *96.*

Allen, E. T.; Day, A. L., s. (336).

22. Alpha. Appareil—pour la découverte des objects métalliques enfouis dans le sol. GC **71,** 312/3, 1917. *199.*
22*a*. Alvarez, A. C. BS **15.** 159/67, 1925. *265.*

[1] The numbers in bold type (**10**) refer to the volume, the numbers in ordinary type (10) refer to the pages. The numbers in italics (*10*) at the end of the reference refer to the page in this book where the reference is mentioned.

Ambronn, Richard
23. Bu **11**, 1918. *168, 195.*
24. He 1920, 113/7. *196, 356.*
25. Technik und Industrie (Zürich) 332/9, 1920. *195, 196, 356.*
26. Gl **57**, 481/8, 1921. *196, 356.*
27. Ka **15**, 197/206, 1921. *106, 195, 196, 356.*
27*a*. Pe **17**, 1921. *57, 191, 356.*
28. JH **3** (2), 27/46, 1921. *4, 57, 125, 180, 196, 250.*
29. ZaG **1**, 3/24, 33/9, 1922. *4, 57, 196, 356.*
30. Um **26**, 529/32, 766/9, 1922; **27**, 55/9, 1923. *127, 128, 161, 356.*
31. DRP 417869 (10. 9. 24). *240.*
32. DRP 419967 (11. 9. 24). *118.*
33. Das technische Blatt (Frankfurt a. M. **7**, 50/2, 98/100, 1925. *82, 86, 88, 105, 137, 175, 180, 188, 250, 356.*
33*a*. DRP 423972 (12. 1. 25), 423973 (17. 2. 25). *191, 240.*
33*b*. Pe **23**, 589/95, 1927. *5, 191, 356.*
33*c*. ZG **2**, 247/51, 1926. *5, 180, 356.*
33*d*. DRP 438794 (2. 3. 25). *128, 129.*
33*e*. Engg **123**, 405/6; AÖCH **44**, 109/11, 1927.; KB **7** Nr. 2; TB **16**, 420/3; *172, 191, 356.*
33*f*. ZFP **35**, 85/7, 1927. *231, 241, 243.*
33*g*. MM 1925, 138/46; MI **153**, 297/8; CI 1926 427/30; KB **6**, 121/5 1926. *356.*
33*h*. Franz. Pat. 618852 (13. 7. 25). *243.*
33*i*. GB **19**, 5\58, 1928. *137, 140, 175.*
33*k*. JB **1**, 11\12, 1927. *137, 175, 180, 227, 242, 243, 257, 356.*
33*l*. MJ 1928, Feb. 25. *137, 140, 175, 178, 180.*
33*m*. Tc **24**, 73\6, 1928.
Ambronn, R.; Erda, A. G., s. (414), (415).
34. Amerigo, A. NC 6 **2**, 437/44, 1911. *149.*
Ampferer, Otto
35. JGW **56**, 539/622, 1906. *35.*
35*a*. VGW 1918, 38/50. *46.*
36. Na **12**, 1007/14, 1924. *35.*
37. Anderson, J. A.; Wood, H. O. JO **8**, 817/22, 1924; BSA **15**, 1/72, 1925. *236.*
38. Andrade, Jules. CR **161**, 345/8, 1915. *78.*
39. Andrée, K. Ueber die Bedingungen der Gebirgsbildung. Berlin 1914 (101 pp.). *35.*
39*a*. Andreesen, H. Diss. Kiel 1905 (44 pp.). *68, 83.*
39*b*. Andrews, Jas. P. PM 6 **50**, 665/74, 1925. *207.*
Angenheister, G.
40. GN 1906, 110/20. *223.*
41. GN 1906, 357/80. *223.*
42. GN 1913, 565/81. *67.*
43. GN 1920, 11/2; 93/100. *67.*
44. GN 1921, 113/46. *215, 222, 223, 224, 225.*
45. Gl **58**, 1292/3, 1922; MM 1922, 2. Heft. 39/53. *98.*
46. TM **27**, 57/9, 1922. *67.*
47. BSG **1**, 6/7, 1923. *212.*

48. TM **28,** 45/7, 1923. *67.*
49. VDP 3 **5,** 35/6, 1924. *68.*
50. GN 1924, 105/15. *122.*
51. PZ **26,** 305/20, 1925. *64, 70, 222.*
51*a*. ZG **2,** 45, 1926. *21.*
51*b*. ZG **2,** 43/4, 1926. *83.*
51*c*. MM 1926, 26/32. ZG **3**, 28/33, 1927. *58, 212, 248, 259.*
51*d*. Forschängen & Fortschritte **2,** 35, 1926. *356.*
———; Linke, F., s. (960).
52. Angot, A. ABM 1908, 43/110. *73.*
53. Ansel, E. A. ZG **1,** 36/46, 167, 1924/5; **2,** 209/14, 1926. *39, 42.*
53*a*. Appleton, E. V. NL **115,** 382, 1925. *200.*
54. ———; Barnett, M. A. F. El **94,** 398, NL **115,** 333/4, 1925, PrC **22,** 672, Pr S **109,** 621/41, 1925. *201.*
———; Watt, Watson, R. A., s. (1586).
55. ———; Herd, J. F. NL **113,** 237/8, 1924. *122.*
56. Archangelski, A. Go **98,** No. 10 bis 12, 1922. *103.*
57. Arctowski, Henryk. BNL 1924. *282.*
58. Arnold, H. Diss. Göttingen 1909; BG **10,** 269/316, 1909. *246.*
59. Arrhenius, Svante A. Lehrbuch der kosmischen Physik. 2 Bde. Leipzig 1903. *15.*
60. Aschoff, K. Die Radioaktivität der deutschen Heilquellen und ihr Anteil an deren therapeutischer Wirkung. München 1925. *128, 129, 131.*
61. Ashman, G. C. AJ **26,** 119/22, 1908. *120.*
Askania-Werke, A.-G., Berlin-Friedenau.
62. DRP 378323 (5. 8. 22). — DRP 395397 (6. 5. 22). — DRP 372133 (5. 5. 22). *25.*
65. DRP 394876 (3. 5. 23). *25.*
66. DRP 396181 (4. 5. 23). *25.*
67. Atmos, G. m. b. H. DRP 282540 (16. 5. 14) † *14.*
Aubuisson, J. Fr. d' — de Voisins.
68. JM **11,** 517/28, 1801/2; **13,** 113/22, 1802/3. *266.*
69. JM **21,** 119/30, 1807; PM **33,** 320/7, 1809. *283.*
70. Auclair; Boyer-Guillon. CR **169,** 24/6, 1919. *243.*
Ault, J. P.
72. National Geograph. Mag. Washington D. C. 1922. *71, 73.*
73. Sc **133,** 46/7, 1925. *71.*
73*a*. BRC **10** 3, 66/7, 1925. *84.*
Austin, L. W.
74. JT **9,** 498, 1914; El **76,** 246, 1915. *200.*
75. SS, No. 257; ETZ **39,** 38, 1918. *200.*
76. JFr **191,** 619/31, 1921. *202.*
77. JT **19,** 115/26, 1922. *202.*
78. PrR **11,** 3/8, 1923. **14,** 373/6; IWA **16,** 41/6, 457/60, 1926. *201.*
79. TrG IV. ann. meetg. April 1923; BRC **7** 5 No. 41, 124/30, 1924; MR **52,** 220, 1924; BRC **10** 3 60/1, 1925. *202.*
80. PrR **13,** 409/12, 1925. *201.*

Bachmetjew, P.
81. GN 1894, 324/7. *148, 149.*

82. MP 7 **12,** No. 3 (58 pp.) **1901.** *148, 152.*
83. GN 1896, 300/3. *152.*
84. ———; Pentscheff, P. Journ. russ. phys. chem. Ges. **26,** 225/48, 1894; Jph **4,** 581, 1895. *152.*
84*a*. Bachurin, J. BJP **1,** 37/56, 1925. *103.*
85. Backlund, H. GeA 1923, 322/3. *103.*
Bäckström, Helge
86. Ofv 1888, No. 8, 533/51. *140, 270.*
87. Ofv **51,** 545/59, 1894. *140.*
Bädecker, K.
87*a*. AP 4 **22,** 749/66, 1907. *140.*
88. Badior, A. Diss. Marburg 1908. (71 pp.). *270.*
89. Bager, A. Diss. München 1915. (87 pp.). *67.*
90. Bahn, Wilhelm. BG **10,** 519/50, 1910. *88.*
91. Baily, F. PT **122** 2, 399/492, 1832. *8.*
92. Baldit, A. NP **52,** 209/13, 225/8, 241/6, 1924. *121.*
Ballore, F. de Montessus de, s. Montessus.
Bamberger, M.; Mache, H., s. (1014).
93. Bandl, E. PZ **17,** 193/6, 1916. *129.*
Banerji, Sudhansu Kumar.
94. PM 6 **49,** 65/80, 1925. *220.*
94*a*. NL **116,** 866, 1925. *227.*
95. Barfield, R. H. Wireless World and Radio Rev. **15,** No. 274/6, 1925; Ref. ETZ **46,** 1201, 1925. *201.*
Barlow, W. H.
96. PM **34,** 344/7, 1849. *64.*
97. PT 1849 1, 61–72, *147, 154.*
98. Barnett, S. J. Researches Dep. Terrestr. Magnetism **4,** 373/94, 1921; PR 2 **19,** 425/7, 1922. *80.*
———; Appleton, E. V., s. (54).
Barratta, M.
99. I terremoti d'Italia, Torino 1901. *219.*
100. Il terremoto Calabra-Siculo del **28,** 12. 1908. Roma 1909. *217.*
100*a*. Barrell, J. JG **22,** 1914; **23,** 1915. *38.*
Bartels, J.
101. MZ **40,** 301/5, 1923. VM **332,** 45/59, 1925. *63.*
101*a*. MZ **42,** 400 ff, 1925. VM **332,** 23/44, 1926. *64, 67.*
101*b*. Geograph. Jahrbuch **40,** 316/73, 1924/5. *70.*
Barus, Carl
102. MG **3,** 309/67, 1882. *87, 146, 156, 157.*
103. U. S. Geological Survey Bull. 1884. *15, 157.*
104. PrW **6,** 495/8, 1920. *15.*
105. Bateman, A. M. EG **19,** 84/6, 1924. *20.*
Battelli, A.
106. AR **9,** 1/95, 1887. *148.*
107. RL 4 **7,** 403/10, 1891. *146.*
Bauer, Louis A.
108. TM **4,** 33/52, 1899. *69.*
109. TM **7,** 57/8, 1903. *69.*
110. Tm **8,** 97/129, 1903. *67. 69.*

111. 8. Intern. Geograph. Congress Washgtn. 1904. Wash. Goo't Prtg. Off. 1905, 501/2. *97.*
112. TM **9,** 113/33, 1905. *64, 151.*
113. TM **11,** 135/44, 1906. *97.*
114. Sc **27,** 812/6, 1908. *74.*
115. TM **14,** 57/66, 1909. *71.*
116. TM **15,** 11/6, 1910. *67.*
117. TM **15,** 232, 1910. *67.*
118. TM **16,** 113/22, 1911. *70.*
119. PZ **12,** 445/8, 1811. *67.*
120. TM **19,** 1/18, 1914. *75.*
121. The work done by the U. S. Coast and Geodetic Survey in the field of terrestrial magnetism. Festbd. z. 100 jähr. Jubel. d. Coast a. Geod. Survey. Washington 1916. *71.*
122. NL **97,** 493/4, 1916. *67.*
123. PrW **2,** 24/7, 1916. *67.*
124. TM **25,** 145/62, 1920. *151.*
125. TM **27,** 1/30, 1922. *154.*
126. TM **28,** 1/28, 1923. *70, 151.*
126*a*. Pap. pres. Sect. Pan-Pacific Sci. Congr. 1923. Trans. 495/502. *71.*
127. TM **28,** 129/40, 1923. *152, 154.*
128. TM **29,** 205/10, 1924. *94.*
129. PR2 **23,** 303, 1924. *67, 68, 70.*
130. TM **29,** 23/32, 161/86, 1924; PR 2 **25,** 253/4, 1925; NL **115,** 537/40, 1925. *122.*
130*a*. BRC **10** 3 64/5, 1925. *72.*
130*b*. Carnegie Inst. Publ. V. 359/84, 1926. *122.*
131. ———; Fleming, J. A. Researches-Dept. terrestr. magnetism. **2,** 211/78, Washington 1915. *71.*
———; Peters, W. J.
132. PR 2 **19,** 428/9, 1922. *151.*
133. TM **30,** 45/68, 1925. *67.*
134. Baumgärtel, B. BG 8, 494/8, 1907. *33.*
Baumgartner, Andreas von
135. AP 2 **76,** 135/44, WB 1849 (2), 295/301; 1849; **80,** 374/80, 381/3, 1850. *149.*
Bäumler, M.
136. JT **19,** 102/9; **20,** 456/7, 1922; **22,** 2/8, 1923. *202.*
137. EN **1,** 160/7, 1924. *201.*
137*a*. ETZ **47,** 955/9, 1926. *202.*
138. Bavink, B. Diss. Göttingen 1904; NM Beil.-Bd. **19,** 322/466, 1904 *93.*
Becker, A.
139. ZJ **30,** 293/302, 1910; ZB **3,** 331/4, 1910. *117.*
140. Str **14,** 707/14, 1922. *118.*
141. Str **15,** 365/83; GR **14,** 364/74, 1923. *116, 118.*
142. ZC **131,** 209/35, 1923. *131.*
143. ZP **21,** 304/15, 1924. *118.*

Becker, George F.
144. Geology of the Comstoke Lode and the Washoe-District. Monographs of the U. S. Geolog. Survey Ill. Washington 1882. *279.*
145. BGA **19,** 113, 1908. *133, 281.*
146. U. S. Geolog. Survey Bull. 401 (24 pp.) Washington 1909. *106.*
146*a*. BGA **26,** 171, 1915. *133.*
Becquerel, Ant. Cés.
147. AC **56,** 97/107; EC **2,** 93/7, 1834; CR **19,** 1052/69; Archives de l'Electr. **4,** 557/79, 1844; CR **20,** 1509/36; Archives de l'Electr. **5,** 233/69, 1845; CR **22,** 781/8; BU **2,** 32/42, 1846; EC **40,** 449/57 1847; CR **43,** 1101/8; MF **27,** 153/294, 1856. *157.*
148. AC **60,** 164/74; CR **1,** 19, 1835; Taylor, Scientif. Mem. **1,** 414/42, 1837; BU **16,** 143/52; AP 2 **45,** 285/6, 1838. *157.*
149. CR **1,** 17/9; Jn **3,** 251/2, 1835; BU **1,** 155/60, 1836. *149, 156.*
150. BU **1,** 1/15, 197/210, 1836. *156.*
151. CR **38,** 1095/101; EC **62,** 369/76, 1854; CR **41,** 733/5, 1855. *156.*
152. CR **46,** 1183/6, 1858. *272, 274.*
Béhounek, Fr.
152*a*. PZ **27,** 8/10, 536/39, 1926. *121.*
153. Beijerinck, F. Diss. Freiburg 1897; NM Beil.-Bd. **11;** 403/74, 1898. *140.*
Belar, A.
154. EbW 1901/3, Heft 7/8. *239.*
154*a*. EW **1,** 60 ff, 1901/2, *241, 248.*
155. Bellini, E. El **86,** 220/2, 1921. *202.*
156. Belot, Emile. CR **162,** 516/8, 1916. *70.*
Bemmelen, W. van
157. MZ **12,** 321/9, 1895. *68.*
158. PrWA 1908, 242/8, 512/33, 782/9, 1908; Kongl. Akad. v. Wetensch. te Amsterdam. Versl. v. d. Genoot. Verg. d. W. e. Nat. Afd. **16** 2, 435/57, 737/44; **17,** 284/90. *148.*
159. MZ **42,** 143/7, 1925. *68.*
Benndorf, Hans
160. WB **111,** 487/512, 1902. *121.*
160*a*. MW **29,** 1905 (24 pp.); **31,** 1906 (42 pp.). *212.*
161. WB **115,** 425/56, 1906. *121.*
162. WB **115,** 941/82, 1906. *214.*
163. WB **118,** 1163/95, 1909. *121.*
164. WB **119,** 89/100, 1910. *121.*
165. PZ **13,** 83/4, 1912. *214, 260.*
166. WB **122,** 169/88, 1913; MW No. 46. *214.*
167. PZ **26,** 81/91; ZG **1,** 147/52, 1925; WB 14. V. 1925. *150, 151, 152.*
167*a*. PZ **27,** 576/8, 1926. *121.*
168. Bennets, J. PM **3,** 17/8, 1833. *156.*
168*a*. Berg. ZpG **29,** 94, 1921. *198.*
Berget, Alphonse.
169. Jph 2 **7,** 503/18, 1888. *270.*
169*a*. CR **146,** 1065/7, 1908. *59.*
169*b*. Bergholm, C. TT **48,** 178/81, 1918. *171.*
170. Bergström, Gunnar. Sveriges Geologiska undersökning Ser. C No. 259, Årsbok **7,** No. 6, 1913. TT **48,** 182, 1918. *171.*

171. Bergwerksbetrieb. Der — im pr. Staate 1906, I. Steinkohlenbergbau. ZBS **55** (statist. Teil), 106, 1907. *281.*
Bergwitz, Karl
172. Habilitationsschrift Braunschweig 1910. *122.*
173. PZ **13,** 28/30, 1912. *117, 121.*
174. Elster-Geitel-Festschr. 585/600, 1915. *122.*
Berndt, G.
175. AP 4 **38,** 958/86, 1912. *116.*
176. He **26,** 429/45, 449/56, 464/8, 1920. *117.*
177. He **27,** 253/7, 271/5, 281/4, 1921. *117.*
Berroth, A.
177*a*. BG **14,** 215/57, 259/83, 1916. *11.*
178. ZJ **40,** 210/1, 1920. *20.*
179. AN **218,** 431, 1923. *9.*
180. ZG **1,** 89/94, 1925. *15.*
180*a*. HP II. Schweremessungen. pp. 416/86, 1926. *12, 15, 29, 37, 40.*
180*b*. ZG **3,** 1/16, 1927. *47.*
181. Bessel, F. W. AN **10,** 97; AB 1830, 41 ff.; Abhandlungen Bd. **3,** 217ff., 1876. *8.*
181*a*. Betz, O. ZtP **7,** 332/5, 1926. *187.*
182. Bezold, W. v. BB 1897, 414/49. *151.*
183. Bicher, F. AV **26,** 455/60, 1914. *32.*
184. Bidlingmaier, Fr. Deutsche Südpolar-Exped. 1901/3, Bd. **5.** Erdmagnetismus I, Berlin; AH **35,** 198/213, 1907; PZ **11,** 1216/22, 1910; PZ **12,** 926/7, 1911. *67, 81.*
186. Bigourdan, G. CR **176,** 1099/104, 1923. *202.*
187. Biot, A. ABr **44** 1, 203/8, 1925. *227.*
188. Birkeland, Kr. Expéd. Norv. 1899/1900, Christiania 1901. *68.*
189. Birnbaum, A. Ka **18,** 144/8, 1924. *56.*
Bischof, Gustav
190. AP 2 **35,** 209/21, 1835. *267.*
191. EJ **20,** 329/76; **23,** 330/99; **24,** 132/65, 252/300, 1836. *279.*
191*a*. Blanc, L. Bull. Soc. Chim. France (4) **39,** 718/22, 1926. *90.*
192. Blaupot ten Cate, D. H. S. VH **5,** 93/112, BIZ 53/132, 1921. *32.*
Blavier, E. E.
193. AT **11,** 155/63; Jph **3,** 157/65, 1884. *153.*
194. CR **98,** 1043/5, 1884. *147.*
194*a*. Bock. TM **31,** 129/31, 1926. *67.*
Boeckh, H. v.
195. Pe **12,** 817/23, 1917. *58.*
196. Drehwagenmessungen bei Egbell, Budapest 1917. *58.*
Bogujavlenskij, L. N.
197. The petroleum and oil shale industrie, Russland, **2,** 239, 1923. *126.*
197*a*. BJP **1,** 57/68, 1925. *123, 128.*
197*b*. BJP **1,** 69/72, 1925. *126.*
198. Böhm, A. Verhdlgn. geolog. Reichsanstalt, Wien 1884, 161/4. *273.*
199. Böhmländer, Karl Gg. Diss. München, Memmingen 1899. *99.*
200. Bois, H. du. RP **2,** 460, 1900. *90.*

201. ——— Reymond, A. du; Hahnemann, H.; Hecht, H. ZtP **2,** 1/8, 33/40, 1921. *241.*
———; Rothé, Lacoste; Dammann; Hée, A., s. (1307).
202. Boltwood, B. B. PM **9,** 599/613, 1905. *114.*
203. Bongards, H. PZ **25,** 679/82, 1924. *123.*
204. Börgen. Rep. Intern. Meteorolog. Congr. Chicago 1893. **2,** 207/583, 1895; MZ **12,** 83/4, 1895. *97.*
Born, A.
205. Isostasie und Schweremessung, Berlin 1923; (Ref. Na **12,** 654/6, 1924 Prey). *32, 36, 38, 39, 41.*
206. Beziehungen zwischen Schwerezustand und geologischer Struktur Deutschlands, Leipzig 1924. *38, 41.*
206*a*. Abhl. d. Senkenberg Nat. Ges. **39,** 1925. *41.*
Borne, G. v. d.
207. GN 1904, 440/64. *210.*
208. Habilitationsschrift Breslau 1905. *118, 123, 125, 128.*
209. BG **9,** 378/403, 1908. *241, 247.*
210. ZO **53,** 101/4, 1914. *265.*
Bornemann, K.; Stutzer, F.; Gross, W., s. (1496).
Börnstein; Landolt-, s. (904).
211. Borras, E. VE **16,** 3. Tl., 1909; VE **17,** 261/343, 1912. *41.*
212. Börsch, A. VG **28,** Berlin 1906; VE **16,** 2. Bd. 257/84, 1909; VG **39,** Berlin 1909. *58.*
213. ———; Krüger, L. VG **10,** Berlin 1902; VE **17,** 154ff, 1913. *58.*
Bosch. *234.*
Bosler, J.
214. CR **152,** 342/4, 1911. *154.*
215. CR **156,** 1419/21, 1913. *68.*
Bothe, W.
216. EE 1921, 177/9. *123, 132.*
217. ZP **16,** 266/79, 1923. *118.*
218. Bouguer, P. La figure de la terre etc., Paris 1749. *40, 41.*
Bourgeois, R.
219. RP **3,** 350/70, 1900. *40, 41.*
220. CR **143,** 422/5, 1906. *46, 59.*
Boussinesq, J.
221. CR **160,** 659/700, 1915. *267, 276.*
222. CR **160,** 747/50; **161,** 405/9, 1915. *272.*
Bowie, William
223. CS Spec. Publ. No. 12 (28 pp.), 1912. *38, 41.*
223*a*. AI 4 **33,** 237/40, 1912. *41.*
224. CS Spec. Publ. No. 40, 1917. *41.*
225. JG **25,** 422/45, 1917. *38.*
226. AJ 5 **2,** 1/20, 1921. *39.*
227. PrW **7,** 23/8, 1921. *39.*
228. CS Serial Publ. No. 291, 1924. *37.*
228*a*. BGA 1922, Juni 30. *38.*
229. CS Spec. Publ. No. 99, 1924. *38, 41.*
230. GJ **63,** 26/33, 1924. *41.*

231. NL **114,** 930/1, 1924. *38.*
232. JFr **198,** 181/200, 1924. *38, 39.*
232*a*. CS Spec. Publ. **106,** 1924 (22 pp.). *31.*
232*b*.———; Hayford, John, s. (651). BG **15,** 103/15, 1926. *38.*
Boyer-Guillon; Auclair, s. (70).
Boys, C. V.
233. RP **3,** 306/49, 1900. *8.*
233*a*. PrS **46,** 253/68, 1890. *21.*
Brammer, E.
233*b*. ZJ **45,** 576/9, 1925. *79.*
233*c*. ETZ **47,** 168, 1926. *201.*
Branco, W.
234. JW **50,** 607/54, 1894. *278.*
235. JW **53,** 28/55, 1897. *279.*
235*a*. Brand, Johann. ZG **1,** 348/59, 1925. *210, 260.*
236. Brandes, Hermann. Diss. Kiel, 1905. *126, 128.*
237. ———, K. A. Akad. Abh. Helsingfors 1888 (120 pp.). *153.*
238. Braun, Ferd. AP 2 **153,** 556/63, 1874. *140.*
239. ———; Waitz, K. JW **48,** 1/12, 1892. *279.*
240. ———, K. JR **9,** 204/35, 1912. *122.*
241. Brauns, O. ETZ **46,** 1350/1, 1925. *172.*
242. Brazier, C. E. CR **176,** 958/60, 1923. *101.*
242*a*. Breisig, F. TF **14,** 93/8, 1925. *172.*
Breit, G.
243. PR 2 **25,** 589, 1925. *202.*
243*a*. BRC **10** 3, 62/4, 1925. *202.*
244. ———; Tuve, M. A. NL **116,** 357, 1923. PR 2 **28,** 554/75; JWA **16,** 98, 1926. *201.*
244*a*. Bridgman, P. W. A.I. 4 **45,** 243/68, 1918. *36.*
245. Briggs, L. J. PR 2 **5,** 184/5, 1915; PrW **2,** 399/407, 1916. *15.*
245*a*. ———; Owen; Wilson. Trans. N. Engl. Inst. Mg. Ing. **74;** 123/41, 1924. *283.*
Brillouin, M.
246. RG 1900, 875/82. *41.*
247. MF **23,** No. 3 (230 S.) 1908. *58.*
248. Brinckmeyer, G. Ka **19,** 138/41, 1925. *163.*
———; Haalk, G., s. (617).
249. Broderick, T. M. EG **13,** 35/49, 1918. *104.*
250. Brodmärkel. AH **50,** 285, 1922. *100.*
251. Broun, John Allan. PrE **4,** 411/2, 1862. *14.*
252. Brown, F. H. EW 1902, 130. *167.*
252*a*. Broxon, I. W. PR 2 **27,** 542/54, 1926. *122.*
253. Brucchietti, G.; Umani, Ant. RL 7 1891 2, 393/9. *146.*
Brückmann, W.
254. VM No. 258, Abhdl. **4** No. 9 (26 pp.), Berlin 1913. *72, 101.*
255. Ber. Pr. Meteorol. Inst. i. d. J. 1917, 18, 19, Anh. 111–116, 1920, No. 305. *274.*
Brunhes, B.
256. AMé 1907, 181/2. *149.*

257. RS **8,** 647/52, 1907; CR **147,** 25, 1445/6, 1908; CR **151,** 409/11, 1910. *149, 150.*
———; David, P.
258. CR **133,** 155/7, 1901. *96.*
259. Jph 4 **2,** 202/5, 1903. *101.*
260. CR **146,** 878/80, 1908. *72, 101.*
261. CR **149,** 74/6, 1909. *149.*
262. ———; Marchand, E. AMé **55,** 181/2, 1907. *149.*
Brush, Charles F.
263. PrA **60,** 43/61, 1921; **61,** 167/83, 1922; **62,** 75/89, 1923; PR 2 **18,** 125/6, 1921. *9.*
263*a*. PrA **64,** 36/50, 1925. *9.*
264. Bryan, Kirk. JG **32,** 499/59, 1924, *279.*
Bryant, W. W.; Chapman, S., s. (294).
265. Bubnoff, S. v. ZaG **1,** 144/9, 1923; **1,** 247/9, 1924. *103.*
266. Büchler, M. MZ **19,** 205, 1902. *273.*
267. Büchner, E. H. JR **10,** 516/31, 1913. *114, 117, 125.*
268. Bücky, A. v. PZ **6,** 536/45, 1905. *81.*
Budig, W.
269. PZ **11,** 596/8, 1910. *121.*
270. VM No. 292 Tätigkeitsber. 1916, 67/73, 1917. *121.*
271. Buehler, H. A.; Gottschalk, V. H. EG **5,** 28/35, 1910; **7,** 15/34, 1912. *157.*
272. Burbank, J. E. TM **10,** 23/49, 1905. *141, 148.*
273. Bureau, R. CR **178,** 556/8, 1924; **180,** 529/32, 1925. *202.*
274. Burkhardt. Entwicklungen nach oszillierenden Funktionen usw. 2 Bde. Leipzig 1908, (Jahresber. d. Deutsch. Mathem. Vereinigg. Bd. 10. Heft 2). pp. 526/670. *207.*
274*a*. Burmeister, F. PG **70,** 268/70, 1924. *73.*
Burrard, S. G.
275. Survey of India, Dept., Prof. Pap. 5, Dehra Dun 1901. *46, 59.*
276. PT **205,** 289/318, 1905; VE **17** 1, 306/16, 1912; PrS **91,** 220/38, 1915; GJ **52,** 237/48, 1918. *42, 46, 59.*
277. Trigon. Survey of India. Prof. Pap. 17. 1901. *38.*
278. Burton, E. F. PM 6 **8,** 498/508, 1904. *126.*
279. Busch, B. Ka **13,** 202/3, 1923. *283.*
280. ———, H. JT **8,** 554/75, 1914. *200.*
281. Butterworth, S. PT **224,** 141/84, 1924. *188.*
281*a*. Büttner, K. ML 1926, 52/4; ZG **2,** 153/9, 187/91, 254/6, 291/3, 1926. *122.*

Cabeen; Kerr, s. (805a).
282. Cady, W. G. TM **9,** 69/80, 1904; **11,** 145/52, 1906; PZ **7,** 710/3; 1906. *77.*
283. Cancani, A. VS **2,** 1903; BG Erg. Bd. **2,** 281/3, 1903. *216.*
283*a*. Capperera. El **5,** 133, 1880. *150.*
284. Carlberg. JA **108,** 115/32, 1924. *46.*
Carlheim-Gyllensköld, V.
285. Déterminations des éléments magnétiques de la Suède méridionale, Stockholm 1889. *74, 183.*

286. Observations magnétiques faites par Th. Aroidson sur les côtes de la Suède 1860/61, Stockholm 1895. *74, 100.*
287. A brief account of a magnetic survey of the iron ore field of Kiirunavaara, Stockholm 1910; Sammanfattning af hufoud resultaten af magnetiska undersökningar vid Kiirunavaara malmfält i Norrbottens län, utförda under åren 1900–1905. OO & J. *87, 103, 105.*
288. Amp. **10,** 9, 1915. *66.*
289. Amp. **11,** No. 20, 1/5, 1916. *87.*
Carlgren, W.; Kjellberg, B.; Curtz, O., s. (806).
Chapman, S.
290. MN **79,** 70/83, 1918. *67.*
291. PrS **95,** 61, 1918. *68.*
292. TrP **22,** 341/59, 1919. *67, 68.*
293. Proc. Cambridge Phil. Soc. **21,** 577/94, 1923. *68.*
293*a*. Quart. Journ. Roy. Met. Soc. **52,** 225/36, 1926. *122.*
294. ———; Bryant, W. W. NL **92,** 585, 1914. *76.*
———; Whitehead, T. T.
295. TrP **22,** 463/82, 1922. *152.*
296. TM **28,** 125/8, 1923. *152.*
Chauveau, A. B.
297. CR **139,** 531/3, 1904. *130.*
298. Electricité atmosphérique. Ill. Généralités sur les ions, l'ionization et la radio-activité. La conductibilité et l'ionization de l'atmosphère. Paris 1924 (240 S.). *120.*
Chevallier, R.
299. Jph 6 **4,** 204, 1923; **7,** 92/6, 1926; NL **116,** 515, 1925. *96.*
300. Aph. 10 **4,** 5/162, 1925. *95.*
Chree, C.
301. PrS **96,** 32, 1919. *106.*
302. TM **28,** 33, 1923. BG **15,** 13/25, 1926. *63.*
303. NL **115,** 982/5, **116,** 45, 1925. **117,** 46/7, 1926. *67.*
304. PrP **37,** 5D/15D, 1925. *122.*
304*a*. NL **118,** 273/5, 1926. *65.*
304*b*. Met. Off. Geoph. Mem. London. No. **30,** 269/88, 1926. *71.*
305. Christiansen, C. AP 3 **14,** 23/33, 1881. *269.*
306. Cirera, P. Ricardo. El Magnetismo terrestre en Filipinas, Manila 1893. *74.*
307. Clark, W. B. Maryland Geolog. Survey. Spec. Publ. Vol. V. pt. 1. Baltimore 1902. (Ref. TM 8, 90/2, 1903.) *97.*
308. Claxton, Thomas F. PrS **76,** 507/11, 1905. *97.*
309. Close, C. F. GJ **47,** 464/7, 1916. *46, 59.*
Colin, R. P.
310. CR **138,** 1076/9, 1904; **140,** 1219/22, 1905. *88, 97.*
310*a*. CR **134,** 958/61, 1274/8, 1339/41, 1902. *102*
311. Colwell, R. C. PR 2 **25,** 589, 1925. *202.*
312. Comité Météorologique international. Caractère magnétique de chaque jour. De Bilt (Pays-Bas). *65.*
313. Compton, Arthur H. PM 6 **39,** 659/62, 1920. *133.*
314. Conklin, R. USA Pat. 1 241197; EngG 1917, 339/40. *199.*

Conrad, V.
315. MZ **23,** 1/2, 1906. *153.*
316. Dynamische Geologie. Enzyklop. d. mathem. Wissensch. VI, **1,** 11, pp. 397–496. Leipzig 1924. *207.*
316*a*. ZG **2,** 34/5, 1926. *223.*
316*b*. MW **59,** Wien 1925 (23 pp.) *259.*
317. Cordier, Louis. MF **7,** 473/556; AFr **2,** 53/138, 1827; EJ **4,** 273/90; **5,** 277/92; **6,** 32/46; SJ **52,** 265/303, 1828. *266.*
318. Cortie, A. L. MN **76,** 15/8, 1915; MN **82,** No. 3; ObL **45,** No. 574, 1922; MN **83,** 204/15, 1923. *67.*
319. Costanzi, G. RF 1910. *31.*
320. Cotta. Gangstudien oder Beiträge zur Kenntnis der Erzgänge. Bd. I. Freiberg 1850. *156.*
320*a*. Cotter, J. R. PM 6 **48,** 458/64, 1924. *281.*
320*b*. Courant, R. Na **14,** 61/4, 1926. *178.*
320*c*. Cox, A. H. PT **219,** App. 73/135, 1919. *101.*
Cox, H.; Strahan, A., s. (1490).
320*d*. Craig, E. H. Cunningham. Bull. Americ. Assoc. Petroleum Geologists. **9,** 165/7, 1925. *46, 357.*
Creak, E. W.
321. PrS **40,** 83/93, 1886. *74.*
322. PT **187,** 345/81, 1896. *74, 102.*
323. Crosthwait, L. Publ. Survey of India, Prof. Pap. No. 13, Dehra Dun 1912; VE **17,** 318, 1912. *38.*
324. Curie, P. Traité de radioactivité I u. II. Paris 1910. *107.*
Curtz, O.; Kjellberg, B.; Carlgren, W., s. (806).

325. Dadurian, H. M. AJ 4 **19,** 16/22, 1905. *119.*
Daft; Williamson, s. (1525).
326. Dahlblom, Th. Om magnetiska fyndigheter och deras undersökning medelst magnetometer. Falun 1898. (Deutsche Uebers. von P. Uhlich, Freiberg 1899.) *84, 103.*
327. Dale, J. B. PM 6 **43,** 463/71, 1922. *230.*
327*a*. Daly, R. A. AJ 5 **5,** 349/71, 1923. *267.*
Dammann; Rothé; Lacoste; Bois; Hée; s. (1307).
328. Darton, N. H. U. S. Geological Survey Bulletin **701,** 1920. *283.*
329. Darwin, G. H. PM 5 **14,** 409/27, 1882. *30.*
Daubrée, A.
330. CR **21,** 1335/6, 1845. *278.*
331. CR **117,** 265/7, 1893. *282.*
332. Daunderer, A. PZ **8,** 281/6, 1907. *153.*
David, P.; Brunhes, B., s. (258), (259), (260), (261).
333. Davidson, E. GJ **63,** 241/3, 1924. *31.*
Davison, Ch.
334. BS **11,** 95, 1921. *216.*
334*a*. A History of British earthquakes, Cambridge 1924. *219.*
Davy, N.; Shaw, P. E., s. (1437).
335. Day, A. L. JG **32,** 459/460, 1924. *279.*
336. ———; Allen, E. T. JG **32,** 178, 1924. *279.*

Dechevrens, P. Marc.
337. CR **167,** 552/5, 1918; **169,** 985/8, 1919; **175,** 1424/6, 1922; TM **23,** 37/9, 145/7, 1918; ABr **42** 1, 117/37, 1922. *152.*
337*a*. CR **168,** 572/5, 1919. *150.*
338. Deckert, E. ZGE 1902, 367/89. *219.*
Deecke, W.
339. NM Beil.-Bd. **22,** 114/38, 1906. *41, 88.*
340. NM Festbd. 1907, 129/58. *41.*
341. BF **18,** 57/65, 1910. *41.*
342. Defforges. VE 1887, Anhg. Vc; Mém. d. Dépôt Gén. d. la Guerre **15** (194 pp.); Jph 2 **7,** 239/50, 347/64, 455/78, 1888. *12, 14.*
343. De Geer, Gerard. Verhdlg. Intern. Geolog. Kongr. Stockholm 1910, Bd. 2, 849/62; PG **58,** 121/5, 1912. *33.*
343*a*. DeGolyer, E. EG **13,** 275\301, 1918. *282.*
344. De la Rive. BU **1,** 152/5, 1836. *156.*
345. Dellinger, J. H.; Whittemore, L. E. Journal Washington Acad. **11,** 245/59, 1921; Kruse, E., SS Bd. **19,** No. 476, 193/230, 1923; ETZ **46,** 1050, 1925. *202.*
346. Demmler, O. JT **12,** 38, 1917. *200.*
346*a*. Dewell, H. D.: Andrews, R. E., Manwaring, C. T. BS **15,** 175/221, 1925. *265.*
347. Dickson, H. N. PrE **8,** 530/6, 1886. *149.*
Dieckmann, Max
348. DRP 303912 (30. 7. 15). *194.*
349. Experimentelle Untersuchungen aus dem Grenzgebiete zwischen drahtloser Telegraphie und Luftelektrizität. I. Die Empfangsstörung. (73 pp.) Berlin 1912. *202.*
350. Dienert, F.; Guillerd, A. Ra **7,** 60/2, 1910. *131.*
Diesselhorst, H.; Hobson s. (726).
———; Scheel, K., s. (1354).
351. Dieterici, C. PZ **18,** 402/4, 1917. *68.*
352. Dlongatch. Rm **20,** 836/7, 1923. *103.*
353. Dorcey, N. Ernest. JO **6,** 633/8. 1922. *114.*
Dorn
354. SK **13,** 37/88, 1872; MZ (Wien) **8,** 113/9, 1873. *272.*
355. AP 3 **9,** 513/52; **10,** 46/77, 1880. *152.*
355*a*. Dorno, C. Licht und Luft des Hochgebirges, Braunschweig 1912. *130.*
———; Kähler, K. s. (796*a*).
356. Dorsey, N. E. TM **18,** 1/38; PR 2 **1,** 240/1, 1913. *84, 85.*
Dougier, R.
357. CR **175,** 1430/2, 1922. *101.*
358. CR **177,** 1133/5, 1923. *101.*
359. Downey, Melvina. PR 2, **16,** 420/37, 1920. *122.*
360. Drygalski, Erich von. ZGE **22,** 169/280, 1886. *35.*
361. Drysdale, C. V. PT **224,** 95/140, 1924. *188.*
362. Duane, W.; Laborde, A. CR **150,** 1421/3, 1910. *117.*
Duckert, P.
362*a*. ML **15,** 55, 292/6, 1926. *202.*
362*b*. IZ **46,** 71/3, 1926. *237.*

———; Heiland, C., s. (678).
363. Dufet, H. CR **81,** 628/31; Assoc. Franç. CR **4,** 403/6, 1875. *140.*
364. Duffield, W. G. MN **1,** 161/204, 1924. *16.*
365. Duffing, G. Erzwungene Schwingungen bei veränderlicher Eigenfrequenz und ihre technische Bedeutung. (Sammlung Vieweg 41/42) Braunschweig 1918. *237.*
366. Dufour, L. AG **26,** 35/60, 1866. *156.*
Dunker, E.
367. NM 1877, 590/606; (u. Krusch) ZpG **4,** 417/33, 1896. *267, 275, 276.*
368. NM 1889, 1, 29/47. *275, 276.*
368*a*. Ueber die Wärme im Inneren der Erde und ihre möglichst fehlerfreie Ermittelung. Stuttgart 1896. (242 pp.) *275, 276.*
369. Duschnitz, B. He **20,** 529/35, 1914. *195.*
Dutton, Cl. E.
370. U. S. Geolog. Survey, IX. Ann. Rep. 1887/88 Washington 1889. JWA **15,** 359/69, 1925. *37.*
371. Bull. Washington Phil. Soc. **11,** 51/64, 1892. *37.*
372. Dyck, G. van. Utrecht, Kgl. Nederl. Meteorol. Instit. Medd. Vertr. No. 27, 1922. *63.*

373. Ebermayer, Ernst. FA **14,** 379/99, 1891; MZ **12,** 169/75, 1895. *272.*
Evert, H.
374. MB **33,** 1, 133/68, 1903. *120.*
375. MZ **21,** 212/3, 1904. *129.*
376. Magnetische Kraftfelder, Leipzig 1905. *139.*
377. MB **36,** 527/43, 1906. *68.*
378. PZ **10,** 346/50, 1909. *120.*
379. Eblé, L. CR **175,** 494/6, 818, 1922; **178,** 1201/2, 1924; **180,** 14 ff, 1925. **182,** 1400/2, 1926. *101.*
———; Maurin, Ch., s. (1059).
———; Labrouste, H., s. (1060).
379*a*. Eccles, W. H. NL **115,** 26, 1925. *201.*
Eckersley, T. L.
380. NL **115,** 496/7, 942, 1925. *200.*
380*a*. Radio Rev. **2,** 60/5, 231/48, 1919. JT **21,** 162/88, 1923; *201.*
380*b*. NL **117,** 380/1, 1926. *201.*
380*c*. Radio Rev. **1,** 421, 1920; JT **18,** 375, 1921. *201.*
380*d*. Eggert. ZV **42,** 474/83, 505/17, 1913; Jordan, Handb. d. Vermessungskunde 1916, 3. Bd. 749/55. *20, 54.*
381. Ehlert, R. BG **3,** 350/475, 1896. *234, 242.*
382. Electricité. L'application de l' — à la prospection des gîtes métallifères, Le Génie Civil **71,** 360, 1917; (MgM 1924, 346/9). *199.*
383. Elias, G. J. TN **2,** 1/14, 1923. EN **2,** 351/8, 1925; TN **3,** 1/21; JT 27, 66/73, 1926. *201.*
384. Ellis, W. NL **44,** 127/8, 1891. *155.*
Elster, J.; Geitel, H.
385. PZ **2,** 560, 590, 1901; **3,** 305, 1902; **4,** 96, 522, 1903. *121, 122.*
386. PZ **3,** 574/7, 1902. *118.*

387. ZJ **24,** 193/201, 1904. *112.*
388. TM **9,** 49/61, 1905. *129.*
389. Wissenschaftl. Beil. z. Jahresber. d. herzogl. Gymn. z. Wolfenbüttel 1907; Weltall **8,** 249/58, 1908. *133, 281.*
390. JR **10,** 323/39, 1913. *110, 113, 127.*
391. Emmons, William H. Engg **115,** 122/3, 1923. *158.*
392. Endrös, Ludwig. Diss. München 1909. *120.*
393. Engler, C. ZE **11,** 714/22, 1905. *117.*
394. ———; Koenig, A. PZ **17,** 73/5, 1916. *117.*
395. ———; Sieveking, H.; Koenig, A. PZ **15,** 441/7, 1914. *117.*
Eötvös, Roland von
396. AP 3, **59,** 354/400, 1896. *20, 75, 88.*
397. RP **3,** 371/94, 1900. *20, 75, 88.*
398. VS **1,** 177/9, Rome 1906. *58.*
399. VE **15** (1906), Beil. 19, 1. Teil 337/95, 1908. *19, 20, 26, 47, 50, 54, 59.*
400. Resultate d. wissensch. Erforschung d. Balaton-Sees 1908. I. 1 geophys. Anh. 1/64. *20, 54, 58, 101.*
401. VE 16 (1909), Anl. A 19, 319/50, 1910. *20, 26, 48, 101.*
402. VE 17 (1912), Anh. A. 40, 427/38, 1914. *20, 23, 25, 48, 52, 53.*
403. ———; Pekar, D.; Fekete, E. AP 4 **68,** 11/66, 1922. *8.*
Erda, A. G.
404. DRP 406299 (21. 11. 20) † *152.*
405. DRP 392189 (13. 12. 21) † *165.*
406. DRGM 803081 (5. 12. 21) † *83.*
407. DRP 405473 (24. 12. 21). *197.*
408. DRP 404098 (8, 11. 22). *197.*
409. DRP 392158 (11. 6. 22). *162.*
410. DRP 367634 (14.2. 22) † *146.*
411. DRP 400148 (26. 3. 22). *182.*
412. DRP 421899 (28. 2. 24). *74.*
Erda, A. G.; Ambronn, R.
414. DRP 349456 (29. 1. 21). *76.*
415. DRP 372536 (17. 6. 21). *162.*
Erforschung des Erdinneren, G. m. b. H.
416. DRP 273815 (12. 7. 13) † *198.*
417. DRP 287611 (12. 12. 13) † *168.*
418. DRP 287610 (12. 12. 13) † *199.*
419. DRP 291133 (16. 3. 15) † *198.*
Erhard
420. JS 1885, 160/74. *157.*
421. JS 1885, 175/82. *156.*
421*a*. Erikson, H. A. JTr. **200,** 506/6, 1925. *123.*
422. Eriksson, B. Akadem. Afhdl. 8 4 (61 pp.), Upsala (Ref. NR **22,** 53, 1907). *90.*
423. Erman, P. AB 1831, 269/84. *266.*
Errulat, F.
424. SK **63,** 1922 (59 pp.); Ge **31,** 608, 1922. *258.*

425. GA **1,** 53/4, 107, 266/8, 1923. *227.*
426. GA **1,** 104/6, 1923. *219.*
427. GA **2,** 219/50, 1923; Gl **47,** 1091, 1924; SK **64,** 30/41, 1926. *99.*
428. Erskine-Murray, J. TF **9,** 465, 1920. *200.*
Eschenhagen, M.
428*a*. BB 1894, 1165/72. *69.*
429. BB 1896, 956/66; BB 1897, 678/86; TM **3,** 136, 1898. *68.*
430. Fo **9,** 1/20, 1898. *74, 88, 98.*
431. TM **4,** 261/71, 1899. *69.*
432. TM **6,** 59/61, 1901. *82.*
433. VDP **1,** 147/52, 1903. *68.*
Esclangon, E.
434. CR **150,** 41/4, 139/42, 1910. *41.*
435. CR **154,** 1316/9, 1912. *41.*
436. Eucken, A. AP 4 **34,** 185/221, 1911. *271.*
436*a*. Eve, A. S.; Adams, Fr. D. NL **76,** 269, 1907. *133.*
437. ———; McIntosh, Dr. TrR 3 **4,** 3, 69/70, 1910. *125.*
Everett, J. D.
438. BR 1859 2, 245/8. *266.*
438*a*. TrEd **22,** 429/39, 1861. *272.*
439. BR 1892, 129/31. *266.*
440. Everling, E.; Wigand, A. AP 4 **66,** 261/82, 1921. *150.*
441. Evershed, J. NL **108,** 566, 1921. *67.*
Ewing. *234.*

442. Falta, W.; Schwarz, G. Berliner Klinische Wochenschrift **48,** 605/6, 1911. *128.*
443. Faraday, M. PT 1851, 7/28; 1852, 25/56; AP 2 **88,** 557/70, 1853. *92.*
444. Faris, R. L. TM **15,** 93/105, 1910. *67.*
445. Farr, C. Coleridge. A magnetic survey of the Dominion of New Zealand and some of the outlying islands for the epoch June 30, 1903 (64 pp.), Wellington 1916 (Ref. NL **100,** 453/4, 1918). *74, 102.*
446. Faye, H. CR **103,** 99, 841, 1886. *35.*
Fekete, E.; Eötvös, R. v.; Pekár, D., s. (403).
447. Fennema, R., Natuurk. Tijdschr. voor Nederl.-Indië **56,** 59/80, 1907. *32.*
448. Fenner, Cl. N. JG **33,** 193/223, 1925. *32.*
449. Fessenden, Reginald R. U.S.A Pat. 1240328. *241, 248.*
450. Field, Arthur M. PrS **76,** 181/4, 1905. *101.*
451. Finke, W. Diss. Göttingen 1909; AP 4 **31,** 149/68, 1910. *92.*
Fiock, E. F.; Rodebush, W. H., s. (1295a).
Fischer, F.; Reich, M., s. (1290).
Fisher, Osmond
452. Great Trigon. Survey of India Vol. 18, Anh. 1, 3/8, Dehra Dun 1906; AJ 4 **21,** 216/20, 1906. *46, 59.*
453. AJ **37,** 199, 1914. *32.*
454. Fisk, H. W. TrG 4. ann. meetg. 1923; BRC **7,** 118/20, 1924. *74.*
455. Fleiss, Chr. PZ **12,** 391/8, 1911. *239.*

Fleming, J. A.
456. TM **16,** 1/12, 1911. *76.*
457. TM **29,** 149/53, 1924. **31,** 27/31, 1926. *65.*
457*a*. IWA **16,** 109/32; RG **37,** 454/67, 1926. *67, 70, 71, 122.*
457*b*. IGV **5,** 122, 1925. *80.*
———; Bauer, L. A., s. (131).
Fletcher, Arnold L.
458. PM 6 **20,** 36/45, 1910. *125.*
459. PM 6 **23,** 279/91, 1912. *124.*
460. PM 6 **26,** 674/7, 1913. *114.*
———; Joly, J., s. (785).
Folgheraiter, G.
461. RS **31** 2, 294 ff., 1882. *101.*
462. RL 5 **3** 2, 117/22, 1894; **4** 1, 203/11, 1895. *95, 96.*
463. RL 5 **5** 2, 293/300, 1896; **6** 1, 64/70, 1897. *96.*
464. RL 5 **8** 1, 176/83, 269/75, 1899. *96.*
465. RL 5 **8** 1, 121/29, 1899. *96.*
466. RL 5 **8** 1, 69/76, 1899. *96.*
467. Fontaine, L. Aph 8 **17,** 418/36, 1909. *237.*
468. Forbes, John. TrC **2,** 159/217, 1822. *266.*
469. Forchhammer, G. AP 1 **42,** 476/79, 1837. *33.*
469*a*. Fordham. MgM **34,** 25/8, 1926. *167.*
470. Förstemann, F. C. AP 2 **16,** 106/36, 1859. *95, 96, 97.*
471. Förstmann, W. A. VR **1,** 4/13, 1844. *96.*
472. Forstmann, W. Pr **27,** 613/6, 1916. *195.*
473. Fouqué, F.; Lévy, Michel. MF **30** No. 2 (pp. 57/77); CR **102,** 237, 1290, 1886. *207, 242, 246.*
474. Fourier, M. Théorie analytique de la chaleur, Paris 1822. *267.*
Fox, Robert W.
475. TrC **2,** 14/8, 19/28, 1822; **3,** 313/28, 1828. *266, 276.*
476. PT 1830, 399/414; Boué, Journ. de Géol. **2,** 385/99, 1830; Edinb. Annal. Sci. **4,** 263/73; AP 2 **22,** 150/3; AJ **20,** 136/43, 1831; TrC **4,** 21/8, 1832; BR 1835, 572/4; PT 1835 1, 39/40; BR 1837, 81/2; EJ **28,** 267/71, 1840. *155, 156.*
477. PrS **3,** 123/5; PM **1,** 310/4, 1832. *104.*
478. TrS 1834, 50/6. *84.*
479. PM 3 **9,** 387, 1836; StA **1,** 133/4, 1836/7; PM **11,** 203/4, 1837; Proceed. Geolog. Soc. **3,** 9/10, 1842. *157.*
480. PM **10,** 171/2, 1837. *157.*
481. BR 1838, 133/7. *149, 156.*
482. PM **23,** 457/9, 491/6, 1843; TrS 1842, 103/9; Ch **4,** 337/9, 1843; Proceed. Geolog. Soc. **3,** 755/7, 1842; StA **1,** 71/6, 1843. *155, 156.*
483. ———; Jordan, T. B. StA **3,** 288/97, 1838/9. *84.*
484. ——— Fr. PrS **76,** 29/33, 1905. *273.*
484*a*. ——— Franchi, S. Boll. R. Comm. Geol. d'Italia **21,** 10/4, 1890. *101.*
Franchi, S.; Oddone, E., s. (1192).
Frech, F.
485. PG **53,** 245/60; NR **22,** 397/400, 1907. *219.*

486. AF **8,** Erdbeben und Baukunst, Berlin, 1913. *176, 265.*
486*a*. Friedl, K. ZBB **35,** 121/32, 145/58, 169/84, 1927. *187, 191, 192.*
487. Friedländer, J. BG **11,** kl. Mitt. 84/95, 1912. *268, 269, 278.*
Friedrich; Schiffner; Weidig, s. (1362).
487*a*. Fritsch, K. von. Diss. Göttingen 1862. *157.*
Fritsche, H.
488. Ueber die Bestimmung der geogr. Länge und Breite und die drei Elemente d. Erdmagn. durch Beob. z. Lande, sowie erdmagn. u. geogr. Messg. an mehr als 1000 versch. Orten in Asien und Europa, ausgef. i. d. J. 1867/91. Petersburg 1893. *100.*
489. BNM **7,** 381/419, 1894. *100.*
489*a*. CI **46,** 687/93, 1925. *101.*
490. Frivold, O. C. AP 4 **68,** 356/68, 1922. *90.*
491. Froley, J. W. TM **8,** 185/7, 1903. *97.*
492. Fuji, Kyôtoku. PrT 2 **8,** 13/4, 1915. *126.*
493. Fulda, Ernst. Ka **17,** 33/6, 1923. *56.*
493*a*. Furtwängler, Ph. EM IV **2,** 1/61, 1908. *12.*
———; Kühnen, F., s. (877).

494. Gaetano; Platiana, Giovanii. MZ **23,** 317/8, 1906. *96.*
Gale, H. G.; Michelson, A. A., s. (1102).
Galitzin, Fürst Boris
495. CRS **2,** Heft 3, 1907. *234.*
496. CRS **3,** Heft 1, 1/106, 1908. *233, 240.*
497. CRS **3,** Heft 1, 117/171, 1908; Heft 2, 5/119, 1909. *225, 228.*
498. BAP 1908, 1223/33. *240.*
499. CRS **3,** Heft 1, 173 ff., 1908. *240.*
500. BG **10,** kl. Mitt. 86/92, 1909. *227.*
501. CR **150,** 901/4; CRS **3,** Lfg. 2, 143/95, 1910. *240, 265.*
502. CRS **3,** Lfg. 3, 1/76, 1910. *234.*
503. CRS **4,** Lfg. 1, 1910. *233, 240.*
504. BAP 1911, No. 14, 983/1006; VS **4,** Conf. Ill. 122/32, 159/77, Manchester 1911. *32, 245.*
505. BAP 1911, 1019/28. *214.*
506. BAP 1911, 941/57. *218.*
508. CRS **4,** Lfg. 2, 1/34, 1912. *245.*
509. CRS **5,** Lfg. 1, 1912. *239.*
510. Zur Frage der Bestimmung der Herdtiefe eines Bebens usw., Petersburg 1912. *221.*
511. VS **4,** 178, Manchester 1911; CRS **4,** Lfg. 3, 50/74, 1912. *216.*
512. Ueber einen neuen einfachen Federseismographen, Petersburg 1913. *236.*
513. BAP 6 **7,** 449/74, 1913. *245.*
514. Vorlesungen über Seismometrie, Petersburg 1913 (Deutsch v. O. Hecker, Leipzig 1914, Spanisch v. Inglada Ors.). *207, 215, 223, 227, 230, 233, 234, 236, 240, 247, 265.*
515. CRS **1,** Lfg. 3 (112 pp.), § 9 pp. 49 ff.; Lfg. 1, 101/183, § 10 pp. 162 ff. *245.*
516. CR **161,** 281/304, 304/8, 1915. *242.*

516*a*. CRS **7,** Lfg. 2, 1917. *214.*
517. Galle, A. VG **61,** Berlin 1914. *11, 27, 28, 46, 59.*
Gallus, A.; Koenigsberger, J., s. (840).
Gauss, K. Fr.
518. Intensitas vis magneticae ad mensuram absolutam revocata. Commentarii Societatis Scientiarum Gottingensis, VIII, 15. 12. 1832. *61, 62.*
519. Gesammelte Werke Bd. 5. Göttingen 1867. *61, 62.*
520. ——; Weber, W. Resultate aus den Beobachtungen des magnetischen Vereins im Jahre 1838. Leipzig 1839. *70, 84.*
521. Gavat, I. Analele Minelor **9,** 209/12, 1926. *20.*
522. Gay Lussac, L. J. ACh **22,** 415/29; PM **62,** 81/9, 1823. *204.*
523. Geiger, H.; Makower, W. Messmethoden auf dem Gebiete der Radioaktivität. (Die Wissenschaft 65.) Braunschweig 1920. *108, 110, 120.*
524. Geiger, L. GN 1910, 331/49. *211.*
525. ———; Gutenberg, B. GN 1912 623/75. *108, 211.*
———; Wiechert, E., s. (1616).
———; Zoeppritz, K., s. (1668).
526. Geikie, Archibald. QJ **70,** 111/5, 1904. *32.*
527. Geitel, H. Die Radioaktivität der Erde und der Atmosphäre. Handbuch der Radiologie (Er. Marx) Bd. I. Leipzig 1920. *124.*
———; Elster, H., s. (385), (386), (387), (388), (389), (390).
528. Geitler, J. Elektromagnetische Schwingungen und Wellen. 2. Aufl. (Die Wissenschaft 6). Braunschweig 1921. *193.*
Gella, N.
529. DRP 403494 (15. 1. 20). *179.*
530. TB 8. 10. 1921. *179, 191.*
531. ZBB **33,** 167/8, 1925. (Um **29,** Heft 3, 1925.) MJ **153,** 324; AÖCh **44,** 64/6, 1926. *139, 169, 179, 180, 186, 191.*
532. Gerdien, H. PZ **6,** 465/72, 1905. *121.*
533. Gernet, A. v. Na **12,** 350/2; Reval, Topo-Hudrograafia Aastaraamat 1924, 75/81, 101/6. 1926, 70/96. *71.*
Gesellschaft f. drahtlose Telegraphie m. b. H.
534. DRP 297920 (29. 5. 15) † *240.*
535. DRP 305574 (24. 11. 17) † *199.*
536. DRP 377187 (5. 2. 20) † *197.*
Gesellschaft für prakt. Geophysik m. b. H.
537. DRP 407495 (7. 4. 22). *199.*
539. DRP 377837 (22. 7. 22). *185.*
540. DRP. 393644 (4. 8. 22). *178.*
541. Geussenhainer, O. Diss. Göttingen 1921; Ausz. im Jahrb. d. philos. Fakult. Göttingen 1921. No. 18. S. 73. *224, 230.*
Gherardi, S.
542. NC **16,** 1862; Bologna, Mém. Accad. Sci. **12,** 515/46, 1861; Bologna, Rendec. 1861/2, 112/4. *97.*
543. NC **18,** 1863; Bologna, Mém. Accad. Sci. **3,** 151/71, 1863; Bologna, Rendec. 1864, 71/5. *96.*
544. Bologna, Mém. Accad. Sci. **5,** 399/411, 1865; Bologna, Rendec. 1866; 87/92. *96.*

Gherzi, R. P. E.
545. Observ. de Zi-ka-wei, notes de sismologie No. 5, 1924. (15 S.); ZG **1,** 163/5, 1925. **2,** 159, 1926. *227.*
546. Observ. de Zi-ka-wei, notes de sismologie No. 6 (21 pp.) 1925. *224.*
Gibault, G.; Maurain, Ch.; Salles, E., s. (1062a).
547. Gibson, A. Engg **114,** 1064/9, 1922. *104.*
548. Giese, W. ETZ **6,** 48/22, 1885; die internationale Polarforschung, Bd. I. Die Beobachtungsergebnisse der deutschen Stationen. Berlin 1886, S. 413ff. *68.*
548*a*. Gil y Ruiz, Rodrigo. IZBE **35,** 62/5, 1927. *357.*
549. Gilbert, Grove Karl. U. S. Geolog. Survey, Prof. pap. 85 bis C 29/36. 1913. *46.*
550. Girard. GnF 1844, No. 5. *99.*
551. Girousse. CR **170,** 841/3, 1313/5, 1920. *155.*
Gish, O. H.
552. TM **28,** 89/108, 1923; IWA **14,** 120, 1924; Ann. Rep. Carnegie Inst. **205,** 1926. *141, 148.*
553. PR 2 **25,** 254, 1925. *141, 152, 167.*
553*a*. Ann. Rep. Carnegie Inst. **224,** 1926. *141, 148.*
553*b*. BRC **11,** 86/91, 1926. *148, 167.*
553*c*. IGU **5,** 155/6, 1925. *152.*
———; Rooney, W. J., s. (1298).
554. Glockemeyer, G. ME **21,** 165/73, 189/202, 1924. *357.*
Gockel, A.
555. PZ **9,** 304/6; MZ **25,** 410/2, 1908. *128.*
556. Die Luftelektrizität. Methoden und Resultate der neueren Forschung. Leipzig 1908. *121.*
557. JR **7,** 487/527, 1910. *123.*
558. TM **17,** 1/20, 1912. *153.*
559. VDP **13,** 850, 1911; MZ **29,** 128/9, 1912. *150.*
560. Die Radioaktivität von Boden und Quellen. (Sammlung Vieweg Heft 5.) Braunschweig 1914. *108, 117, 118, 123, 124, 125, 126, 131.*
561. PZ **16,** 345/52, 1915; MZ **33,** 15/24, 1916. *130.*
562. PZ **25,** 646/7, 1924. *130.*
563. PZ **25,** 381/90, 1924. *122.*
564. Das Gewitter. 3. Aufl. Berlin 1925. *121, 122.*
565. JT **25,** 131/4, 1925. *201.*
565*a*. TM **31,** 81/7; BG **15,** 26/37, 1926. *122.*
566. ———; Wulf, Th. PZ **9,** 907/11, 1908. *125, 130.*
567. Goldreich, A. H. MR **15,** 15/6, 1923. Die Bodenbewegungen im Kohlenrevier und deren Einfluss auf die Tagesoberfläche. Berlin 1926. (307 pp.) *33.*
Goldschmidt, V. M.
568. ZK **44,** 545/60; **45,** 490/4, 1908. *125.*
569. ZE 1922, 411 ff.; Vidensk. Selskabs Skrifter M.-N. Kl. No. 11, Kristiania 1922. *267.*
———; Haber, s. (620).
570. Göllnitz, O. JS 1911, 1/89. *81, 99.*

572. Gorjanović-Kramberger; Steeb; Melkus. JGW **60,** 1/66, 1910. *279.*
573. Görnemann, M. Mitteil. d. physik. Versuchs-Station Halle-Kröllwitz **24,** 1910. *200.*
Gornick, H.
574. Erzausschuss Bericht No. 2, Verein Deutsch. Eisenhüttenleute, Sitzung v. 15. 12. 21. Gl. **62,** 878, 1926. *20, 57.*
575. ZJ **43,** 306/7, 1923. *20.*
Gottschalk, V. H.; Buchler, H. A., s. (271).
576. Graatz, F. BJ **6,** 31, 1925. *265.*
577. Graber, H. V. VGW 1902, 144/50. *36.*
578. Gradenwitz. Engg **118,** 54/6, 1924. *357.*
578*a*. Graetz. Handbuch der Elektrizität und des Magnetismus, Leipzig. *143.*
579. Graham, J. J. JCT **104,** 920/1, 1922. *274.*
580. Grand-Ry. RMM **7,** 126/54, 1925. *357.*
581. Graves, J. JST **2,** 102/23, 1873. *152.*
Gray; Milne, J., s. (1115).
582. Greiss. AP 2 **98,** 478/87, 1856. *102.*
583. Grengg. ZBB **31,** 173/6, 1923. *357.*
———; Schumann, R., s. (1409a).
584. Griesser, R. Diss. Freiburg 1921. *106.*
Gross, W.; Stutzer, F.; Bornemann, K., s. (1496).
585. Gruber, Ludwig. RE **19,** 271/82, 1883. *84.*
Grunmach, L.
586. VP 1886, 58/64. *226.*
587. VDP 1908, 583; PZ **10,** 853/8; BB 1909 2, 969/80; AP 4 **30,** 951/73, 1909. *226, 240, 243.*
588. Experimentaluntersuchung zur Messung von Erderschütterungen. Verhdl. d. Vereins z. Förderung d. Gewerbefleisses, Berlin 1913. Heft 2 bis 5. *226, 243.*
589. Gube, Felix. Diss. Halle, 1910 (52 pp.). *128, 230.*
590. Gubkin, J. Go **98,** Heft 10–12, 1922. *103.*
591. Gudden, B. Diss. Göttingen 1919 (41 pp.); ZK **56,** 422/3, 1921. *125, 132.*
Guillerd, A.; Dienert, F., s. (350).
592. Günther, R. D. Contributions to the study of earth-movements in the Bay of Naples. Oxford-Rome 1903. *32.*
———, S.
593. BG **2,** 71/152, 1895. *227.*
594. Handbuch der Geophysik. Bd. I. Stuttgart 1897. *14, 15, 61, 266, 267, 273.*
595. ———; Adami, F. MB 1912, 121/36. *99.*
Guschkoff; Schewjakoff; Tanatar; Kissjelnikoff, s. (1361).
Gutenberg, Benno.
596. PZ **11,** 1184/5. 1910; **15,** 591/3, 1914; **16,** 285/7, 1915; AH **48,** 402/4, 1920. *227, 228.*
597. Diss. Göttingen; BG **11,** 314/53, 1912. *225, 226, 227, 228, 230.*
598. GN 1914, 125/76. *211.*
599. VSt 1914 (1921); AH **51,** 287/90. 1923. *226, 227, 228.*

599*a*. VSt 1915, 1. Beiheft. *224.*
600. VSt 1915, **1.** *218.*
601. ZaG **1,** 65/75, 1923. *220, 258.*
602. ZaG **1,** 105, 1923. *212.*
603. PZ **24,** 296/9, 1923. *211.*
604. PZ **24,** 458/9, 1923. *223.*
605. GA **1,** 3/13, 1923. *223.*
606. PZ **25,** 377/81, 1924. *222, 223, 224.*
607. ZG **1,** 69/70, 165/6, 1924/5. *227.*
608. VJ Heft 3, 10/48, Jena 1924. *227.*
609. Die seismische Bodenunruhe und ihr Zusammenhang mit den Nachbargebieten, insbes. Geologie und Meteorologie. Berlin 1924 (69 pp.). *225, 227, 228.*
610. Na **13,** 360/2, 1925. *212.*
611. Der Aufbau der Erde, Berlin 1925. *11, 36, 39, 212, 267.*
612. PZ **26,** 258/60, 1925. *258.*
613. ZG **1,** 94/108, 1925. *212, 220, 222.*
613*a*. ZG **2,** 24/9, 1926. *212.*
613*b*. Abh. d. Senkenb. Natf. Ges. **40,** 57/88, 1925. *211, 213, 217, 222, 223, 224.*
613*c*. PZ **27,** 111/4, 1926. *222, 223, 224.*
613*d*. Lehrbuch der Geophysik, Berlin 1926/7. *11, 15, 20, 37, 48, 52, 148, 167, 171, 202, 203, 204, 207, 211, 216, 223, 225, 230, 234, 236, 238, 240, 246, 250, 259.*
613*e*. BG **15,** 51/63, 1926. *204, 211, 220, 225, 230, 240, 259.*
Gutenberg, Benno; Geiger, L., s. (525) (s. a. BG **13,** kl. Mitt. 198/203, 1914).
———; ———; Zoeppritz, K., s. (1668).

Haalck, H.
614. ZaG **1,** 257/80, 1924. *212.*
615. ZtP **6,** 377/80, 1925. *85, 185.*
616. ZtP **6,** 262/5, 1925. ZI **47,** 16/32. 1927. *83, 85.*
616*a*. ZG **2,** 1/11, 49/62, 1926. *106.*
616*b*. ZG **2,** 293/7, 1926. *25.*
617. ———; Brinckmeier, G. ZaG 1, 116/120; Ka **17,** 241/5, 1923. *88, 105.*
618. Haanel, Eugène. Ottawa, Dept. of the Interior. 1904 (132 pp.). *104.*
618*a*. Haarstick. MM 1926, 56/71. *20.*
Haasemann, L.
619. ZJ **22,** 98/103, 1902. *15.*
619*a*. VG No. 19, Berlin 1905. *59.*
620. Haber; Goldschmidt. ZE **12,** 49/51; ETZ **27,** 794/5, 1906. *144.*
620*a*. Haberland, G. ETZ **48,** 456/8, 1927, *172.*
621. Hadamard. Propagation des ondes, Paris 1903. *202.*
622. Hadley, H. M. BS **14,** 6ff, 1924. *265.*
623. Hahn, F. G. Ueber das Aufsteigen und Sinken der Küsten. Beitrag z. allg. Erdkunde. Leipzig 1879, (227 pp.). *32.*
623*a*. Hahn, Otto. Was lehrt uns die Radioaktivität über die Geschichte der Erde. (64 pp.) Berlin 1926. *132.*
624. ——— Otto; Rothenbach, Martin. PZ **20,** 194/202, 1919. *110.*
625. Hahnemann, W.; Hecht, H. PZ **17,** 601/9, 1916; PZ **22,** 353/60, 1921. *241.*

——— ———; Bois-Reymond, A. du, s. (201). Haid, M.
626. ZJ **16,** 193/6, 1896. *14, 15.*
627. VE **15** 1, 268/72, Budapest 1906. *42, 47.*
Hall, Lawr. P.; Richards, Th. W. *s.* (1292*a*).
Hallock. s. (773).
628. Hamer, R. PR 2 **23,** 303/4, 1924. *152.*
Hammer, E.
629. Ueber den Verlauf der Isogonen im mittleren Württemberg. Stuttgart 1886. *99.*
630. PG **49,** 284/5, 1903. *32.*
631. PG **58,** 319/20, 1912. *31.*
632. PG **60** 2, 195/6, 1914. *46, 59.*
633. PG **70,** 125, 1924. *38.*
634. ——— R. Misviisnings undersögelser ved Bornholms kyster. Kjóbenhavn (Tijdskr. f. sóvaesen, Nye raekke **27,** Heft 6, 1892. *100.*
635. Hammer, W. PZ **13,** 943/5, 1912. *117.*
636. ———; Vohsen, Fr. PZ **14,** 451/4, 1913. *117.*
637. ——— W. DRP 391777 (1. 7. 21) † *16.*
637*a*. Hancock. Colliery Engg. **3,** 499/503, 1926. *197.*
638. Hann, J. Lehrbuch der Meteorologie. 3. Aufl. Leipzig 1915. (847 pp.) Erscheint zurzeit in Lieferungen neu. (4. Aufl. bearb. v. Süring.) *272.*
639. Harker, A. PrC **10** 5, 268/78, 1900. *101.*
640. Harrassowitz, H. Gl **58,** 788, 1922; ZpG **31,** 14, 1923. *357.*
Haussmann, Karl.
641. Die erdmagnetischen Elemente von Württemberg und Hohenzollern, gemessen und berechnet für 1 . 1. 01. Stuttgart 1903. *69.*
642. AB 1904, Anhang. Abhdlg. 4. (138 pp.). *99.*
643. MM Heft **7,** 32/51, 1905. *99.*
644. ZJ **26,** 1/15, 1906. *76.*
645. VS **4,** 197/203, 1911. *33, 224, 258.*
646. PG **59,** 11/5, 64/8, 119/21, 179/84, 1913. *69, 73, 98.*
647. ÖV 1914, No. 3. *357.*
648. PG **68,** 177/80, 1922. *73.*
649. ZG **1,** 129/33, MM 1925, 31/41. *73.*
649*a*. Hayden, H. H. Rec. geol. Surv. of India **43** 2 Calcutta 1913. *42.*
650. Hayford, J. F. PrW **8,** 25/40, 1906. Bull. Philosoph. Soc. of Washington **15,** 57/74, 1907. The figure of the earth and isostasy from measurements in the U. S., Washington 1909. *38, 41.*
651. ———; Bowie, W. CS, Spec. Publ. No. 10, Washington 1912 (132 pp.). *38, 41.*
———; Tittmann, O. H., s. (1543).
Hazard, D. L.
652. Ref. üb. Passalsky, P. T.: TM **7,** 46/7, 1902. *103.*
653. CS, Terr. magn. S. No. 126; Spec. Publ. 33 II. Washington 1920. CS. Spec. Publ. **116,** (50 pp.) 1925. *73, 102.*
654. Tr.G, 4. ann. meetg. 1923. BRC **7,** 115/7, 1924. *88.*
654*a*. BRC **10** 3, 67/8, 1925. *72.*
654*b*. CS. Spec. Publ. **117,** (52 pp.) 1925. *70.*

Hecht, H.; Hahnemann, W., s. (625)
———; ———; Bois-Reymond, A. du, s. (201).
Heck, N. H.
655. TM **27,** 169/71, 1922. *102, 104.*
656. TrG, 4. ann. meetg. 1923, BRC **7,** 5, 121/2, 1924. *104.*
Hecker, O.
657. ZJ **16,** 1/16, 1896. *234.*
658. BG **4,** 98/104, 1900; BG **6,** 87/97, 1904. *246.*
659. BG **4,** 59/67, 1900. *12.*
660. ZJ **21,** 81/3, 1901. *233.*
661. VG **29,** Bln. 1906 (112 pp.) *225, 227.*
662. VG No. 11, 1903 (137 pp.); VZE No. 16, 1908; No. 20, Bln. 1910, (160 S.). *16.*
663. VS **3,** 22, Zermatt 1909. *228.*
664. ZGE 1909, 36/88. *46.*
665. ZJ **30,** 6/14, 1910. *20.*
666. VE **16** 2, Anl. 15. 310/8, 1911. *20.*
667. MS **2,** 13/32, 1913; BG **13,** 1914; MS **2,** No. 1, 1/13, 1915; MS **2,** No. 3, 1916. *228, 229.*
668 and 668*a*. MS **1,** No. 5, 1914, Beil. z. BG **13,** 1914. *30, 36, 226.*
668*b*. VJ Heft 2, 1922 (18 pp.) *258.*
669. MS **2,** No. 2, 28/33, 1915. (BG **14**). *229.*
670. BG **14,** MS **2,** No. 1, 14/16, 1915. *26, 211, 233.*
Hecker, O.; Koenigsberger, J., s. (811).
Hée; Rothé; Lacoste; Bois; Dammann, s. (1307).
Heiland, C.
671. Diss. Hamburg 1923; ZpG **32,** 1924; GA **3,** 206/80, 1924. *126, 357.*
672. ZF **32,** 213/6, 1924. *20.*
673. ZDG **76,** 101/11, 1924. *105.*
674. ZJ **45,** 417/36, 1925, (Engg. **121,** 47/58, 1926). *15, 23, 24, 82, 104, 105, 248, 250, 357.*
675. ZJ **45,** 89/95, 1925. *20, 25, 26.*
676. ZL **45,** 244/7, 1925. *48.*
677. ZG **1,** 118/9, 1925. *20.*
678. ———; Duckert, P. ZaG **1,** 289/315, 321/9, 1924. *82.*
679. Heiligtag, Th. Diss. Jena 1923; JT **21,** 77/100, 1923. *201.*
679*a*. Heilmann, W. Maschinenbau 1922, 210/15. *242.*
Heilmann, W.; Jahnke, E., s. (759).
Heim, Alb.
680. EH **10,** 489, 1908. Jahrb. d. Schweiz. Alpenklubs **53,** 1918. *42.*
681. EH **15,** 24/5, 1916/8. *42.*
681*a*. Heine. PZ **27,** 219/24, ME **33,** 495/500, 1926. Elektrische Bodenforschung, Berlin, 1928. *137, 171.*
682. Heise, F. Bu **16,** 226 f, 1923. *357.*
Heiskanen, W.
683. Veröffentl. d. Finnischen geodät. Institut. No. 4, 1924. (Ref. Na **13,** 535, 1925). No. 5, 1926. *11, 37, 41.*
684. ZG **1,** 225/7, 1925. *37.*
685. Hellmann, G. VM **215,** Abhdl. **3,** No. 3, (60 pp.) Berlin 1909. *67, 73.*
686. Hellwig, Karl. Diss. Göttingen, 1924. *198.*

Helmert, F. R.
687. Die mathematischen und physikalischen Theorien der höheren Geodäsie. 2 Bde. Leipzig 1882/4. *11, 37.*
688. VE Nizza 1887, Anh. 1 (53 pp.) Berlin 1888. *59, 97.*
689. VE **16,** 3. Teil; VG u. VZE 1890 (52 pp.). *42.*
690. BB 1896 1, 409/13; VG 1896; VG, NF No. 9, Berlin 1902. *42, 59.*
691. VG u. VZE 1898 (92 pp.). *12.*
692. BB 1901, 328; 1902 2, 843/55; 1903 1, 650/67; 1909 2, 1192/8. *37.*
694. Die Schwerkraft und Massenverteilung der Erde, EM VI, **1** B, 85/177, Leipzig 1910. *11, 20, 37, 38, 40, 59.*
695. BB 1914 1, 440/53. *37, 41.*
696. BB 1915, 676/85. *11, 26.*
Helmholtz, H. v.
697. AP 3 **7,** 337/82, 1879. *152.*
698. Vorlesungen über Elektrodynamik und Theorie des Magnetismus. Leipzig 1907. *141.*
———; Thomson, W.; Tait; Wertheim, s. (1534).
699. Hempel. AMP **65,** 337/62, 1880. *267.*
700. Hengler, L. DP **43,** 81/92, 1832. *234.*
701. Henne. Untersuchungen über die Temperatur des Bodens. Zürich 1894. *272.*
Henning, F.
702. AP 4 **7,** 893/904, 1902. *121.*
703. Diss. Königsberg 1909 (54 pp.). *269.*
Henrich, Ferd.
704. NM 1876 716/23; 1877, 897/905; ZBS **25,** 58/62, 1877. *267.*
705. ZBS **38,** 137/44, 1890. *267.*
706. ZBS **52,** 1/11, 1904. *275.*
Henwood, W. J.
707. TR **4,** 198/9, 1836; BR 1837 2, 36/7. *283.*
708. AFr 3, **11,** 585/604; EJ **22,** 270/81; StA **1,** 124/33, 1837; PrS **4,** 317, 1841; TrC **5,** 445/60, 1843. *156.*
709. Herath. ML Juli 1923, 7/8; AL **14,** 119/27, 1923. *202.*
Herd, J. F.; Appleton, E. V.; Watt, R. A. Watson, s. (55).
710. Hergesell, H. BG **1,** 69 ff, 1887. *35.*
711. Herglotz, G. ZMP **52,** 275/99, 1905. *36.*
712. Heritsch, F. MW **53,** Wien 1918 (42 pp.). *219.*
713. ———; Schwinner, R. MW **57,** Wien 1919 (36 pp.). *215.*
713*a*. Hermant, A. Levé magnetique de la Belgique, Brüssel 1920, *73.*
Herroun, E. F.; Wilson, Ern., s. (1635).
714. Hess, Hans. ZM 1912, 471/9. *207.*
———, Victor F.
715. WA 1918, 274/5; WB **127,** 1297/313, 1918. *129.*
716. TrE **41,** 287/302, 1922. *114.*
716*a*. Die elektrische Leitfähigkeit der Atmosphäre und ihre Ursachen. Sammlg. Vieweg 84/5. (174 pp.); TM **31,** 78/9, 1926. *120, 122.*
716*b*. PZ **27,** 159/64, 405/6, 1926. *122.*
717. ———; Kofler, Martin. PZ **18,** 585/95, 1917; MZ **35,** 157/70, 1918. *123.*

718. Hevesy, G. v. JR **10,** 198/221, 1913. *115.*
719. ———; Paneth, F. Lehrbuch der Radioaktivität, Leipzig 1923. London 1926. *107.*
719*a*. Hewlett, C. W. PR 2 **3,** 469; TM **19,** 127/61, 1914. *129.*
720. Heydweiller, Adolf. AP 4 **12,** 608/21, 1903. *93.*
Heyl, Paul R.
721. SS **19,** 307/24, 1924. *9.*
721*a*. BRC **11,** 53, 1926. *16.*
722. Himmelfarb, A. J. Go **100,** 642/3, 1924. MI **156,** 182/4, 1927. *103.*
723. Himstedt, F. BF **14,** 181, 1903; AP 4 **13,** 573/82; PZ **5,** 210/3, 1904. *126, 281.*
724. Hobbs, W. H. PrA **48,** 259/302, 1909. *265.*
725. ———; Ruska, J. Eine Einführung in die Erdbebenkunde, Leipzig 1910. *207.*
726. Hobson; Diesselhorst, H. Allgemeine Theorie der Wärmeleitung. EM V **1,** 161/231, 1903. *269.*
Hodgson, E. A.
727. BS **13,** 100/4, 1923. *265.*
727*a*. JC **18,** 412/26, 1924. *222.*
728. Hoefer, H. v. EG **7,** 536/41, 1912. *282.*
729. Hoernes, R. Erdbebenkunde. Die Erscheinungen und Ursachen der Erdbeben, die Methoden ihrer Beobachtung, Leipzig 1893. *207.*
730. Hoff, Carl v. Geschichte der durch Ueberlieferung nachgewiesenen natürlichen Veränderungen der Erdoberfläche. Gotha, I, 1822; II, 1824; III, 1834; IV, 1840; V, 1841. *219.*
Hoffmann, G.
731. AP 4 **62,** 738/58, 1920; ZP **7,** 254/9, 1921. *110.*
732. PZ **24,** 475/6, 1923. *110.*
733. PZ **26,** 40/2, 669/72, 1925. *123.*
734. Na **14,** 622, 1004; AP 4 **80,** 779/807, 1926. *122.*
735. Holden, E. S. AJ **35,** 427/31, 1888. *216.*
736. Holmes, A. PrS **85,** 248/56, 1911; GM 1915, 60 ff. NL **116,** 892, 1925. *132.*
Holst, H.
737. Diss. Freiburg 1924. *26, 58.*
738. ZG **1,** 228/37, 1925. *48, 54.*
740. Hoppe, O. BH **43,** 427/8, 1884. *72.*
741. Horn, A. v. AH **41,** 638/9, 1913; **44,** 145/51, 1916. *32.*
742. Hort, W. Technische Schwingungslehre, 2. Aufl., Berlin 1922. *237, 238*
743. Hotchkiss, William Otis. Wisconsin, Geolog. a. Nat. hist. Survey Bulletin 44, Econ. Ser. 19, Madison (Wis.) 1915 (378 S.). *77, 84, 89, 103, 104.*
744. Hough, S. S. PT **187,** 319/44, 1896. *36.*
745. Hövermann, Georg. NM Beil.-Bd. **34,** 321/400, 1912; Diss. Göttingen 1912. *124.*
746. Huber, P. B. WB **127,** 471/88, 1918. *130.*
747. Hubert, F. ZG **1,** 134/43, 197/209, 1925. *210, 249, 259, 260.*
747*a*. Hubert, H. CR **183,** 368/70, 1926. *202.*
748. Hughes. NL **20,** 77/81; PrS **29,** 56/65; PM **8,** 50/6; AT **6,** 497/514, 1879. *93.*

748*a*. Hulburt. J. Fr. **201,** 597/634, 1926. *201.*
748*b*. Hullen, R. JT **20,** 235/39, 1922. *201.*
749*a*. Hülsenbeck. Gl **62,** 1494/6, 1926. *163.*
749. Hülsmeyer, Chr. DRP 165546, 169154 (1904) + *196.*
750. Hummel, K. ZM 1924, 66/71. *149, 158.*
750*a*. Hunkel. Ka **20,** 1/3, 1926. *168.*
Hunt, Rob.
751. PM **19,** 442/5, 1841; GS **1,** 433/59, 1846; WYG **3,** 380/6, 1849/59. *157.*
752. WE **2,** 117/20, 1846. *156.*
753. ———; Phillips, J. TrS 1841, 157/64; 1842, 26/7; Ch **3,** 251/3, 1842. *156.*
754. Himt, J. BS March 1922. *265.*
755. Hurinuzescu, A. Ra **7,** 231/2, 1910. *126.*
756. Huyssen. Verhdl. d. 8. Deutsch. Geogr. Tages zu Berlin 1889, 225/35. *283.*

762[1]. Ibach. AÖCh **44,** 106/7, 1926. *173, 191.*
762*a*. Idrac, P. CR **182,** 1634/5, 1926. *150.*
764. Iliin, B. JT **22,** 122/7, 1923. *202.*
765. Ingersoll, L. R.; Koepp, O. A. PR 2 **24,** 92/3, 1924. *269.*
Inglada, Vicente-Ors
765*a*. Ibérica **7,** No. 356, 1920. *216.*
765*b*. Tall. d. R. Soc. Exp. d. Hist. Natur. **50,** 349/65, 1921. *219.*
766. Talleres del instituto geografico, Madrid 1919 (51 pp.); Ibérica **7,** No. 318, 1920; La corteza terrestre, Tall. d. inst. geogr. Madrid 1923 (94 pp.). *212.*
767. La sismologia . . . sus métodos. El estudo actual de sus problemas fundamentales, Tall. d. inst. geogr., Madrid 1923 (96 pp.). *207.*
768. Nuevas formulas; Tall. d. inst. geogr. y Estad. Madrid 1921 (61 pp.); Tall. d. Assoc. Esp. p. e. progr. d. l. Ciencias, Oporto 89/107, 1921. *220.*
769. Ingenieria y Construcción **1,** No. 11/12, 1923. *250, 265.*
770. Las Observationes gravimetricas, Madrid 1925 (596 pp.); Rev. d. l. Accad. Cien. exact., Madrid, **21,** 169/84, 1924. *20, 52, 54;* s. a. Wegener (1592).
770*a*. Calculo de las coordinadas del foco sismico etc. Madrid 1926; Jb 1926 No. 639. *218, 220.*
770*b*. Mem. Inst. geogr. y catastr. 15. No. VI. Madrid 1926 (36 pp.) *258.*
790. Issel, Ar. BNM **57** 1, 134/9, 1882. *14.*

757. Jäger, G. Theoretische Physik IV. Elektromagnetische Lichttheorie und Elektronik. (Sammlung Göschen No. 374). Berlin-Leipzig 1921. 000.
758. ———; Meyer, Stephan. AP 3 **67,** 707/13, 1899. 00.
758*a*. Jahn; Schnabel. IZBE **34,** 650/3, 1926.
759. Jahnke, E.; Heilmann, W. Ka **15,** 229/34, 1921. 000.

[1] As the German text has not differentiated between I and J, the numerical sequence for these two letters is disarranged. References may be found easily by the alphabetical arrangement which is in correct order.

760. ———; Keinath, G. DP **335,** 119/25, 285/6, 1920; ZBS **69,** 153/84; Ka **15,** 65/9; Gl **57,** 165/9, 1921. *242.*
760*a*. Jakob, Max. AtP **7,** 475/81, 1926. *270.*
Jannettaz, Ed.
761. BGF **2,** 264/7, 1874; **3,** 499/510, 1875; **4,** 553/4, 1876; CR **81,** 1254/7, 1875; **95,** 996/9, 1882. *270.*
762. CR **78,** 1202/5, 1874. *268.*
762*aa*. Jeans, J. H. PrS **102,** 554/74, 1923. *225.*
Jeffreys, H.
762*b*. NL **115,** 876, 1925; The Earth, Cambridge 1924, *267.*
762*c*. BG **15,** 167/88, 1926. *37.*
762*d*. Seismol. Invest. Brit. Assoc. A. 3–4, 1926; MNGS 1, 371/83, 1926. *213.*
762*e*. MNGS **1,** 282/92, 334/48, 1926. *222.*
762*f*. PrC **23,** 472/81, 1926. *206, 222, 251.*
762*g*. MNGS **1,** 321/34, 1926, *206.*
Jeffreys, H.; Wrinch, D., s. (1648a).
763. Jenkins, W. A. PM 6 **26,** 752/74, 1913; PM 6 **41,** 454/62, 1921. *80.*
771. Johannsen, Alb.; Phemister, T. C. JG **33,** 268/71, 1925. *207.*
772. Johansen, N. P. Den Danske Gradmaaling, Heft 2 (155 pp.), Kjóbenhavn 1908; NR **24,** 252, 1909; VE **17,** 239, 1911. *42.*
772*a*. Johnston, H. F. TM **31,** 145/52, 1926. *121.*
773. Johnston, J.; Adams, L. H. EG **11,** 741/62, 1916. *274, 275.*
774. Jolly, Th. v. Am **13** 1, 157/76, 1880; **14,** 1/26, 1883. *8, 19, 20.*
Joly, John
775. Radioactivity and geology, London 1909 (auch NL **78,** 456/66, 1908). *133, 281.*
776. PM 6 **17,** 760/5, 1909; **20,** 353/7, 1910. *114, 129.*
777. PM 6 **20,** 125/8, 1910. *114.*
778. PM 6 **22,** 134/50, 1911. *114.*
779. CRB **1,** 370/91, 1911. *133.*
780. PM 6 **23,** 201/11, 1912. *125.*
781. PM 6 **40,** 681/91, 1920. *36.*
782. NL **109,** 578/9, 1922. *124.*
783. PM 6 **45,** 1167/88, 1923. *32.*
784. NL **114,** 160/4; Na **12,** 693/9, 1924. *114, 124, 129.*
784*a*. Radioactivity and the surface history of the earth, Oxford 1924. *125, 133.*
784*b*. BG **19,** 415\41, 1927. *133, 281.*
785. ———; Fletcher, A. L. PM 6 **19,** 630/49, 1910. *124.*
———; Poole, J. H. J., s. (1248).
786. ———; Rutherford, E. PM 6 **25,** 644/57, 1913. *132.*
787. ———; Smith, Louis B. NL **87,** 101, 1911; SD **13,** 148/61, 1911. *129.*
Jones
788. JCT **107,** 822/3; PrSW **31,** 559/79, 1923; **41,** 157/69; CG **129,** 1069/70, 1925. *282.*
789. JCT **110,** 692; PrSW **41,** 141/55, 386/99, 466; CG **129,** 1137, 1925. *283.*
———, Lancaster, E.; Shaw, H., s. (1434).

789*a*. Jones, E. Lester. JFr **201,** 563/96, 1926. *265.*
Jordan, T. B.; Fox, R. W., s. (483).
Kähler, K.
791. VM **267,** 1913; PZ **15,** 27/31, 1914, *118.*
792. Luftelektrizität. (Sammlung Göschen 649) 2. Aufl. 1921. *120.*
793. Messmethoden der atmosphärischen Elektrizität. Handb. d. biolog. Arbeitsmethoden. (Abderhalden) Abt. II. phys. math. 451/82, 1923. *120.*
794. MZ **40,** 204/11, 1923. *153.*
795. Die Elektrizität der Gewitter. (Sammlung Borntraeger No. 3) Berlin 1924 (148 pp.) *130, 153.*
796. AH **52,** 201/7, 1924. *129.*
796*a*. Kähler, K.; Dorno, C. MZ **42,** 434/9, 1925. *121.*
Kähler, K.; Marten, W., s. (1047).
797. Kalinowski, St. TM **28,** 141, 1923. *100.*
798. Kalitsky, K. BGR **33,** 1107/27, 1914. *106.*
799. Kämtz. Lehrbuch der Meteorologie Bd. II. Halle a. S. 1833. p. 32. *272.*
800. Karrer, Felix. AGW **9,** 1877, 209/16. *279.*
801. Kater, H. PT 1818 1, 33/102. *11.*
801*a*. Kauenhowen, W. ZBB **34,** 536, 1926. *126.*
802. Kayser, E. Lehrbuch der Geologie. I. Allgem. Geologie. V. Aufl. Stuttgart 1918, pp. 57ff. *266, 267.*
Kawamura, Toshio; Watanabe, Nob., s. (1581).
Keinath, G.; Jahnke, E., s. (760).
803. Kelly, Sherwin F. Engg **114,** 7. and 14. 10. 1922; EG **18,** 412/3, 1923. CJ **48,** 10/1, 1927. *158, 165.*
804. Kemp, James F. BGA **33,** 30. VI. 1922. *138.*
805. Kerner v. Marilaun, F. WB **100,** 704/29, 1891. *273.*
805*a*. Kerr; Cabeen. EG **20,** 729/37, 1925. *141.*
805*b*. Kiebitz, F. TF **15,** 207/14, 1926. *200, 274.*
806. Kjellberg, B.; Carlgren, W.; Curtz, O. JA 1894, 432/4. *103.*
806*a*. Kilchling, K. ZG **2,** 134/7, 1926. *26.*
807. King, L. V. JG **20,** 119/38, 1912. *207.*
Kinoshita, S.; Voigt, W., s. (1570).
808. Kinsley, Carl. PR 2 **18,** 151/2, 1921. *202.*
809. Kirsch, Gerhard. Na **11,** 372/80, 1923. *132.*
810. Kirst, E. Gl **59,** 13/4, 1923. *265.*
Kissjelnikoff; Schelojakoff; Tanatar; Guschkoff, s. (1361).
810*a*. Kithil. Engg **122,** 931/6; Explosives Eng. 4, 45/7, 1926. *261.*
811. Kleinhaus, K. PZ **15,** 362/3, 1914. *36.*
Klotz, O.
812. VS I, Haag 1907. *228.*
813. BG **11,** 501/14, 1912. *218.*
814. PO **3,** No. 2. 1, 19/61. Ottawa 1916. *211.*
815. TrR 3 **14,** 47/53, 1920. *246.*
815*a*. Klusche. Archiv Eisenbahnbau 1926, 331/63. *33.*
Knoche, Walter
816. MZ **27,** 76/7, 1910. *129.*
817. PZ **13,** 1221/2, 1912. *129.*

818. MZ **32,** 554/5, 1915. *129.*
819. MZ **32,** 555, 1915. *130.*
820. Knopf, A. Bibliography of isostasy, BRC, Division of Geol. a. Geogr. Washington 1924. *38.*
821. Knott, C. G. The physics of earthquake phenomena, Oxford 1908 (283 pp.). *207.*
822. Kober, L. ÖB 1923, 31/2. *58.*
823. Köbrich. ZBS **41,** 50/1; NR 8, 344; We **10,** 262, 1893. *277.*
824. Koch, A. Erdwärme und Tunnelbau im Hochgebirge, Wien 1882. *273.*
824*a*. ———, K. R. JW **57,** 356/408, 1901. *42.*
825. ———; MJ 1923, 599. *190.*
Koenig, A.; Engler, C., s. (394).
———; ———; Sieveking, H., s. (395).
Koenigsberger, Joh.
826. PZ **7,** 297/300, 1906. *267, 281.*
827. CR du X.me Congr. Géol. Intern. Mexico 1906 (1907), 1127/54. *272, 283.*
828. ZM 1907, 200/3; 1907, 673/9. *266, 268, 269, 283.*
829. EG **7,** 676/707, 1908. *277.*
830. EH **10,** 506/25, 1908. *271, 273.*
831. GR **1,** 241/9, 1910. *133.*
832. BF **18,** 43/56, 1910. *278.*
833. ZpG **30,** 33/41, 124, 1922. *357.*
834. GR **14,** 164/83, 1923. *357.*
834*a*. Gl **59,** 992/4, 1923. *357.*
835. Gl **60,** 499/500, 1924. *141, 283.*
836. Ka **18,** 36, 1924. *282, 283.*
837. Ka **18,** 56/9; Pe **20,** 227/30, 723/5, 1924. ZG **2,** 169/71, 1926. *57, 88, 105, 106.*
838. ZG **1,** 237/42, 1925. *83.*
839. Ka **19,** 353/4, 1925. *357.*
839*a*. ZpG **33,** 169/75, 1925. *20.*
839*b*. Ka 19, 353/4, 1925; ZpG **34,** 151/6, 1926. *127, 168, 357.*
839*c*. ZG **2,** 257/60, 1926. *25.*
839*d*. Pe **22,** 1324/6; ZBB **34,** 1324/6, 1926. *191.*
839*e*. ZBB **35,** 132/5, 1927. *282.*
840. ———; Gallus, A. SE **40,** 1523/4, 1920. *104.*
841. ———; Hecker, O. ZG **1,** 152/9, 1925. *150.*
842. ———; Mühlberg, M. NM Beil. Bd. **31,** 107/57, 1911. *267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 282, 283.*
843. ———; Reichenheim, O. NM 1906 2, 20/40. *141.*
844. ———; Thoma, E.; Leier, F. BF **18,** 1/42, 1909/10. *272.*
845. Koerts, A. Atmosphärische Störungen in der drahtlosen Nachrichtenübermittelung. (Die Hochfrequenztechnik No. 1.) Berlin 1924. (151 pp.) *201, 202.*
Köfler, Martin; Hess, V. F., s. (717).
Kohlrausch, Fr.
846. AP 2 **142,** 547/59, 1871. *79.*
847. AP 3 **17,** 737/72; GN 1882, 84/9. *80.*

848. AP 3 **15,** 533/50, 1882; **19,** 130/43, 1883; MB **13,** 1/16, 1883. *79.*
849. AP 3 **29,** 47/52, 1886. *79.*
850. AP 3 **60,** 336/9, 1897. *68.*
851. Lehrbuch der praktischen Physik. Leipzig und Berlin. *140, 147, 269.*
———; Schweidler, E. v., s. (1415).
851*a*. Kohlschütter, E. AGA **5,** No. 1, Göttingen 1907 (229 pp.). *42.*
852. Kolb. ÖB 1902. *282.*
Kolhörster, Werner
853. Aerophysik. Forschungsfonds Halle Abh. **14;** VDP **16,** 719/21, 1914; BA **7,** 87, 1915. *122.*
854. ZP **5,** 107/10, 1921. *122.*
855. Die durchdringende Strahlung in der Atmosphäre. (Probleme der kosmischen Physik, No. 5), Hamburg 1924 (72 pp.). *110, 122, 123, 126.*
856. ZJ **44,** 333/49, 1924. PZ **27,** 62/3, 1926. *122.*
857. ZJ **44,** 494/7, 1924; PZ **26,** 654/7, 1925. *117.*
858. BB 1925, 120/5. *122.*
858*a*. Na **14,** 290/5, 313/20; ZP **36,** 147/9, 1926. *122.*
858*b*. Kolhörster, W.; Salis, G. v. Na **14,** 936; ZaC **39,** 1214/5; NL **118,** 518, 1926. *123.*
858*c*. Köppen, W. Geograph. Zeitschr. **25,** 39/48, 1919. *38.*
859. Körber. HE **3,** 87/90, 1891. *99.*
860. Koristka, Karl. HB **6,** 139/49, 1850. *72.*
Kossmat, F.
861. AAL **38,** 2, 1/62, 1920; GR **12,** 165/89, 1921. *35, 41.*
861*a*. LB **78,** 35 ff; GR **17,** 385/91, 1926. *38.*
862. Kotô, B. On the cause of the great earthquake in Central Japan, 1891. Tokyo, 1892. *31.*
862*a*. Kovarik, A. F.; McKeehan, L. W. Radioactivity BRC **51,** 1/203, 1925. *107.*
Kövesligethy, R. v.
863. VS 1901; BG Erg. Bd. **1,** 281/9, 1902. *230.*
864. Seismonomia, Boll. Soc. Sismolog. Italiana. **11,** No. 5–6, 1906. *220.*
865. VS **1,** Anhg. 25, Rom 1906. *223.*
Kowatscheff, J. D.
866. AN **203,** 237/60, 1916. *16.*
867. AN **221,** 145/58, 1924. *46.*
Krahmann, R.
867*a*. Die Anwendbarkeit der geophysikalischen Lagerstätten-Untersuchungsverfahren usw. Halle 1926(37 pp.). (AÖCh **44,** 22/5, 1926.) IB **1,** 203/8; ZBB **34,** 750/1, AÖCh **44,** 30/2, 1926. *10, 138, 139, 141, 169, 179, 180, 186, 191, 192, 357.*
867*b*. ZpG **34,** Heft 1, ME **23,** 230/7, 583/6, 1926. *105, 179, 191.*
Kranz, W.
868. NM Beil. Bd. **28,** 574/610, 1909. *32.*
869. NW **35,** 273/6, 1920. *33.*
870. Kreil, Carl. WB 1849, 278, 347/50; DW **1,** 265/310, 1850. *74, 98.*
871. Kreis, A. AG 1923, 414/6. *220.*

Krenkel, E.
872. Die Bruchzonen Ostafrikas. Tektonik, Vulkanismus, Erdbeben und Schwereanomalien. Berlin 1922 (184 pp.). *42, 219.*
872*a*. ZM 1923, 297/301. *42.*
Krigar-Menzel, O.; Richarz, Fr., s. (1293) (1294).
873. Krüger, L. VG **4,** 134, 1916. *59.*
873*a*. Krumbach, G. ZG **2,** 30/3, 1926. *258.*
Krusch, P.
874. Gerichts- und Verwaltungsgeologie, Stuttgart 1916. *33.*
875. Untersuchung und Bewertung von Erzlagerstätten. Stuttgart 1921, p. 96. *104.*
876. Str **16,** 575/99, 1624. *123.*
Kruse, S.; Dellinger, J. H.; Whittemore, L. E., s. (345).
876*a*. Kühn, B. ZG **2,** 342/50, 1926. *357.*
877. Kühnen, F.; Furtwängler, Th. VG NF. No. 27, Berlin 1906. *13.*
878. Kunz, J. NM **100,** 62/88, 1907. *90, 95.*
879. Künzli, E. Mater. p. l. carte géologique d. l. Suisse, nouv. sér. livr. **21,** 126/47. *273.*
880. Kupffer. AP 1 **15,** 159/91; ACh **42,** 367/92, 1829. *272.*
Kusakabe, S.
881. PEJ **11, 14,** 1903. *207, 208.*
882. PEJ **17,** 1904. *207.*
883. PEJ **22,** Art. 3, 27/50, 1906. *207.*
884. PrT **2,** 447/54, 1906. *265.*
885. PrT **3,** 110/6, 1906. *207.*
886. K. W. W. ETZ **41,** 179/80, 1920. *199.*

Lacoste; Rothé; Bois; Dammann; Hée, s. (1307).
Laborde, A.; Duane, W., s. (362).
887. Labrouste, H. Aph 9 **19,** 5/62, 1923. *240.*
———; Maurain, Ch.; Eblé, L., s. (1060).
Lacoste, J.
888. CR **175,** 707/8, 1922. *202.*
888*a*. TM **31,** 153/63, 1926. *80.*
889. Lagrange, E. Ciel et Terre, Bruxelles **40,** 80, 1924. *88.*
890. Laibach; Lumière, L. CR **167,** 1068, 1918. *239.*
Lais, R.
891. BG **12,** 45/88, 1913. *219.*
892. Mitteil. d. Grossh. Badischen Geolog. Landesanstalt. **7,** Heft 2, Heidelberg 1914. *217, 265.*
893. ———; Sieberg, A. BG **12,** 186/206, 1912; VJ 1925. *217, 218, 219.*
894. Lallemand, Ch. VE **17,** 289, Hamburg 1912. *31.*
Lamb, Horace
895. PrL **15,** 139/49, 270/4, 1883/4. *172.*
896. PT **203,** 1/42, 1904. *206.*
896*a*. Lambert, W. D. Sc **63,** 242/8, 1926. *11.*
Lamont, J.
897. Resultate des magnetischen Observatoriums in München während der 3-jährigen Periode 1843 bis 1845. p. 5. *80.*

898. Handbuch des Erdmagnetismus, Berlin 1849. *76, 79, 80, 81.*
899. AM 6, 381/482, 1851. *80.*
900. Magnetische Ortsbestimmungen ausgeführt an verschiedenen Punkten des Königreichs Bayern und an einigen auswärtigen Stationen. 2 Tle. München 1854. *72.*
901. Der Erdstrom und der Zusammenhang desselben mit dem Magnetismus der Erde. Leipzig 1862. *148, 154.*
902. Landerer. CR **93,** 588/9, 1881. *153.*
Landolt
903. BB 1908 1, 354/87. *9.*
904. ——— -Börnstein. Physikalisch-chemische Tabellen, V Aufl. Berlin 1923. *8, 11, 141, 143, 268.*
Lapparent, A. de.
905. CR **103,** 772, 1886. *35.*
906. CR **103,** 1040, 1886. *35.*
907. RS **37,** 802, 1886. *35.*
908. Lardry. OE **3,** 254/64, 1924. *201.*
Larmor, J.
909. PrS **82,** 1910, *36.*
909*a*. PM 6, **48,** 1025/36, 1924. *200.*
Larsen, E. S.; Washington, H. S., s. (1580).
Lasareff, P
910. Pétrograd, Annexe Procès Verbaux, Acad. Sci. 1921, 81/93; Berlin, Wissensch.-techn. Abteilg. d. Oberst. russischen Volkswirtschaftsrates im Ausland 1922; Go **98,** Heft 10–12, 1922; CR **178,** 510/3, 1301/2, 1924; TM **30,** 11/4, 1925. BG **15,** 71/89, 91/102, 1926. *87, 103.*
911. Pétrograd, CR Acad. Sci. 1923, 2; Na **11,** 705/8; TM **28,** 123/4, 1923; Jph 6 **5,** 180/91; RG **35,** 582/4, 1924. *103.*
913. CR **178,** 2186/7, 1924. *54.*
914. Jph 6 **5,** 191/2, 1924. *88.*
915. CR **178,** 1991/3, 1924. *87, 103.*
916. CR **178,** 627/30, 1924. **181,** 1150/1, 1925. *87.*
Láska, V.
917. Pe **19,** 539/40, 1923. *58.*
918. Pe **19,** 612/3, 1923. **22,** 241/3, 1926. *58.*
918*a*. ZBB **34,** 1217/19, 1926. *357.*
919. ———W. VS **1,** BG Erg.-Bd. **1,** 209/35, 1902. *226.*
919*a*. Lassen, H. JT **28,** 109/13, 139/47, 1926. *201.*
920. Laub, J. PZ **14,** 81/3, 1913. *129.*
Lautenschläger, L.; Sieveking, H., s. (1447).
921. Lauter, H. Diss. Halle 1915. (37 pp.) *128.*
922. Lauterborn, R. JOG **2,** 10, 1912. *31.*
Lawson, A. C.
922*a*. Geol. Publ. Univ. of California **12,** 431/73, 1921. *31.*
922*b*. NL **117,** 235, 1926. *122.*
——— Rob. W.
923. WB **126,** 722/39, 1917. NL **118,** 478, 1926. *132.*
924. Na **5,** 429/35, 452/9, 610, 709, 1917. *132.*

925. BRC **8** 4, No. 46, 1924 (22 pp.). *38.*
926. Layer, Ernst. MZ **35,** 94, 1918. *130.*
926*a*. Laylander. Engg. **121,** 325/8, 1926. *104.*
927. Le Blanc, M. Lehrbuch der Elektrochemie, 5. Aufl. Leipzig 1911 *145, 147.*
928. Lechner, Alfr. ZJ **35,** 269/73, 1915. *12.*
Lees, Ch. H,
929. PrS **83,** 339/46, 1910. *281.*
930. PrS **91,** 440/50, 1915. *130.*
930*a*. Lejay, P. CR **181,** 678/9, 1925. *202.*
931. Leighton, A. Engg 17. 6. 1919. *240.*
Leimbach, Gotth
932. ETZ **32,** 237/8, 1911. *195, 196.*
933. DRP 273339 (26. 3. 13) †. *197.*
934. DRP 270400 (5. 3. 13) †. *198.*
935. DRP 278385 (12. 2. 13) †; 281 612 (27. 11. 13) †. *199.*
936. Ka **7,** 157ff, 433/42, 1913; ZVJ **58,** 1298/300, 1914; **59,** 771/4. 1915; Gl **51,** 1915; Ka **8,** 157/61, 1914; **11,** 49/51, 1917; Gl **51,** 333/40, 1915. *168, 195, 196.*
937. ———; Löwy, Heinr. DRP 237944 (15. 6. 10) †. *196.*
937*a*. ———; Meier, E. PZ **14,** 447/57, 1913. *196.*
Lemoine, P.
938. CR **148,** 1696/8, 1909. *31.*
939. BGF 4 **11,** 341/412, 1911. *219.*
940. Lemström, K. S. OfvH **41,** 60/104, 1900. *154.*
941. Lenox-Conyngham, G. P. NL **115,** 116, 1925. *15.*
942. Lenz, R. E. BAP **1,** 433/8, 1860; MP 7 **5,** No. 3 (38 pp.), 1862/3. *100.*
Lepape, Adolphe; Moureu, Charles, s. (1140a).
942*a*. Leprince-Ringuet. Ann. Soc. Géol. d. Nord **36,** 67/83, 1907. *281.*
943. Lertes, P. Die drahtlose Telegraphie und Telephonie (Wissenschaftliche Forschungsberichte Bd. 4) Dresden 1923. *193.*
944. Less, Emil. AP 2 Erg.-Bd. 8, 517/55, 1878. *268.*
945. Lesterg, O. C. AJ 4 **44,** 225/36, 1917. *118.*
Lévy, M.; Fouqué, F., s. (473).
946. Lewitzky, G. VS **1**; BG **1,** 305/12, 1902; VS **3,** 22, Zermatt 1909. *227.*
Leier, F.; Koenigsberger, Joh.; Thoma, E., s. (844).
Leyst, Ernst
948. Rm **10,** No. 5, (133 pp.). 1887. *84.*
949. RM **10,** No. 11, (33 pp.), 1887. *78, 79.*
950. SK **33,** 1/67, 1892. *273.*
951. TM **7,** 67/74, 1902. *72, 100, 103, 106.*
952. BNM 1910, 79/212. *79.*
953. The Kursk magnetic anomaly, Moscow 1921. *103.*
954. Lichte, H. ETZ **41,** 88/90, 1920. *188.*
955. Liebenow, C. PZ **5,** 625/6, 1904. *281.*
956. Liebisch, Th. BB 1911, 414/22. *140.*
957. Lincke, G. Aufbau des Erdballes, Jena 1924. (23 pp.). *267.*
958. Lindgren Mineral Deposits, 1913. pp. 77/81. *282.*
958*a*. Lingen, I. St. van der. ZM 1926, 177/83. *124.*

958*b*. Link; Schober. Gas- & Wasserfach **69**, 225/8, 1926. *118, 127, 129, 359.*
959. Linke, F. AGA NF. **7**; Ergebn. d. Arb. d. Samoa-Observ. d. Berlin 1909. *227, 228.*
960. ———; Angenheister, G. AGA NF. **9**, No. 1. Berlin 1911. *97.*
Ljungdahl, G. S.
961. Stockholm, Kgl. Sjökarteverket, Jordmagn. Publ. No. 2. 1922; No. 3, 1924. *100.*
961*a*. Ebda. No. 4, 1925. *100.*
Liznar, J.
962. MZ **20**, 184/5, Wien 1885. *72.*
963. ZJ **8**, 13/6, 76, 1888. *81.*
964. ZJ **9**, 9/15, 1889. *76.*
965. MZ **11**, 30/3, 1894. *78.*
966. MZ **12**, 261/7, 1895. *69.*
967. WB **107**, 753/76, 1898. *72.*
968. TM **5**, 63/72, 121/2, 1900. *80.*
968*a*. Llarena, J. Gomez de. ZG **1**, 182/6, 1925. *218.*
Lloyd, Harold.
969. BR 1835, 557/9. *84*, s. (972).
970. BR 1841 2, 26/7. *67.*
971. Account of the magnetical observatory of Dublin and of the instruments and methods of observation employed there, Dublin 1842. *81.*
972. PrJ **3**, 298/9, 1844/7.
973. PrJ **5**, 1/11, 1850/3. *81.*
974. Treatise on magnetism, London 1874. *82.*
975. Locke. TrA **9**, 283, 1846. *102.*
976. ———, Augustus. EG **7**, 583/7, 1912. *279.*
977. Loewinson-Lessing, F.; Mitkewitch, V. CR **180**, 942/5, 1925. *96.*
978. Loisel, P. CR **171**, 858/60, 1920; **173**, 921/3, 1921; **175**, 890/2, 1922. *131.*
Lorenser, E.; Ludewig, P., s. (998), (999).
978*a*. Lorenzoni, G. VE **17**, 1912, Hamburg, Bd. I, Beil. A 23, pp. 331/2. *14.*
979. ———; Silva, G. VE **17**, 331, Hamburg 1912; Publ. della R. Commissione Italiana, Padova 1912. *14, 15.*
980. Loth, W. A. Brit. Pat. 191389; DRP 417663 (30. 12. 22.). *188.*
980*a*. Lotze, Fr. GN 1927, 75/114. *133, 281.*
Love, A. S. H.
981. Lehrbuch der Elastizität, Deutsch v. A. Timpe, Leipzig 1907. *206, 222.*
982. Some problems of geodynamics, Cambridge 1912. *206, 222, 225.*
Löwy, H.
983. ZM 1911, 573/9; BG **11**, 1911; AP 4 **36**, 125/33, 1911. *140, 143.*
984. ZpG **19**, 284; PZ **12**, 1001/4, 1911; JT **5**, 386 ff., 1911/2; DRP 254517 (13. 4. 11) †; DRP 254478 (2. 4. 12)†; PZ **20**, 416/20, *195, 196, 198.*
985. DRP 368079 (28. 3. 19) †; Elektrodynam. Erforschung d. Erdinneren u. Luftschiffahrt, Wien 1920; ZpG **29**, 93/4, 1921; DRP 401448 (2. 11. 21) †; DRP 403939 (3. 7. 23.). *198.*

986. Löwy, H.; Leimbach, Gotth. DRP 246836 (15. 5. 10) †; PZ **13,** 379/403, 1912. *195, 196*; s. a. (937).
987. Lübben. ZFT **3,** 45/6, 1922. *200.*
987*a*. Lüdemann, K. ZV **54,** 144/51, 1925. *73.*
988. Ludewig, J. ETZ **2,** 7/10, 1881; **5,** 115/9, 147/52, 1884. *153.*
———, Paul
989. AH **42,** 77, 1914; SEZ **13,** 29/40, 1916; JT **12,** 122/55, 1917. *201, 202.*
990. Na **6,** 89/92, 101/3, 1918. *122.*
991. PZ **22,** 298/302, 1921. *117.*
992. PZ **22,** 121/3, 1921. *131.*
993. Radioaktivität (Sammlung Göschen No. 317) (133 pp.), Berlin-Leipzig 1921. *108.*
994. Str **13,** 163/73, 1921; JS 1921, 10/34. *111, 118.*
995. Str **15,** 384/9, 1923. *118.*
996. ZP **20,** 394/7, 1924. *114.*
997. Str **19,** 170/1, 1925. *131.*
———; Lorenser, E.
998. ZP **13,** 284/91, 1923; **21,** 258/63, 1924. *118.*
999. ZP **22,** 178/85; Str **17,** 428/35, 1924. *128.*
———; Witte, H.
1000. ZG **1,** 242/50, 1925. *126, 131.*
1000*a*. ZG **2,** 70/7, 1926, *126, 129.*
Luggin, H.; Tumlirz, O., s. (1552).
1000*b*. Lühr, Wilhelm. Diss. Darmstadt 1923. *172.*
Lumière, L.; Laibach, s. (890).
Lundberg, Hans
1001. TT **49,** 48, 1919; Practical experience in electrical prospecting, Stockholm 1923. *161, 189.*
1002. DRP 328835 (4. 12. 18). *161, 189.*
1002*a*. Geolog. Survey of Sweden, Aarsbook **16,** No. 9, Stockholm 1922; MgM Aug.-Sept. 1923; Engg 5. 4. 1924, 584/5; AÖCh **43,** 166/70, 1925. TT **56,** 320/3, 1926. *189, 357.*
———; Sundberg, Eckholm s. 1500*d*.
1003. ———; Royers. MiM **6,** 229/33, 1925. *161.*
1004. Lutteroth, A. AP 3 **60,** 1081/106, 1898. *95.*
Lutz, C. W.
1005. MB **36,** 507/25, 1906. *121.*
1006. MB 1911, 305/28, 329/60. *150.*
1007. ZaG **1,** 218/22, 1923. *121.*
1008. PZ **24,** 166/70, 1923; **25,** 282, 1924. *117.*
1008*a*. ZG **3,** 34/43, 1927, *211.*
1009. Luyken, Karl. ZaG **1,** 161/81, 1923. *81.*
1010. Lyell, Charles. Principles of geology, 3 Vol., London 1832/3; PT 1835 1, 1/38. *31.*
1011. Macdonald, H. M. PrS **92,** 493, 1916. *200.*
Macelwane, James B.
1012. BS **13,** 109/12, 1923. *217.*
1013. BS **14,** 81/9, 1924. *212.*

Mache, H.
1013*a*. CRB **1,** 540/3, 1911. *131.*
1013*b*. BRC **11,** 65/9, 1926. *211.*
1014. ———; Bamberger, M. WA 1914, 40/5; WB **123,** 325/465. 1914. *114, 117, 125.*
———; Meyer, St.
1015. WB **114,** 355/85, 1905. *131, 281.*
1016. ZJ **29,** 65/8, 1909. *117.*
1017. ———; ———; Schweidler, E. v. WA **42,** 72/5. *114.*
1018. ———; Schweidler, E. v. Die atmosphärische Elektrizität. Methoden und Ergebnisse der modernen luftelektrischen Forschung. (Die Wissenschaft 30), Braunschweig 1909 (247 pp.). *120.*
1019. Machts, L. DRP 330090 (6. 11. 19) †. *196.*
1019*a*. Mc Gee, W. J. AJ 3 **44,** 177/92, 1892. *32.*
Mc Intosh, Dr.; Eve, A. S., s. (437).
Mc Keehan, L. W.; Kovarik, A. F. s. 862*a*.
1020. Mack, K. PZ **21,** 7/11, 1920. *223.*
———; Schmidt, A. v., s. (1395).
Mc Lennan J. C.; Treleaven, C. L., s. (1548).
1021. ———, J. C.; Wright, C. S. PR **24,** 276/84, 1907. *92.*
1022. Mc Millan, M. D. JG **25,** 105/11, 1917. *38.*
Mader, K.
1023. ÖB **5,** 121/6, 1924. *52, 58.*
1024. WB **133,** 117 ff., 1924. *58.*
1024*a*. Madinhac, Mme de; Homery, Mlle. Atlas Magnétique de France. Paris 1926. *73.*
Madinhac, Mme. de; Maurin, Ch., s. (1061), (1062).
Madsen, V. H. O.
1025. VE **17,** 245/8, Hamburg 1912. *15.*
1026. VE **17,** 466, Hamburg 1912. *13.*
1027. Maggi. Verona, Mem. Accad. Agric. **28,** 177/83, 1851. *156.*
1028. Magnetism. Researches of the Department of Terrestrial,—. Washington 1912; II. ibid. 1915. *71, 75, 85.*
1029. Magnus Gustav. AP 2 **22,** 136/49, 1831; **40,** 139/45, 1837; BU **13,** 194, 1838. *275.*
Mainka, C.
1030. ZF, 1907; Mechaniker **17,** 61/5, 1909; MPG **4,** 633/67, 1912; ZF **11,** 91/2, 99/101, 108/11, 116/8, 124/5, 132/3, 140/2, 149/50, 1915; ZFP **1,** 99/105, 1922. *234, 236, 239.*
1031. VSt 1909. *245.*
1032. PZ **14,** 555/7, 1285/6, 1913. *228.*
1033. ZF 1916. *233.*
1034. PZ **20,** 574/9, 1919. *214.*
1035. ZtP **3,** 145/52, 241/9, 1922. *237, 243.*
1036. Physik der Erdbebenwellen, Berlin 1923 (157 pp.). *207, 220, 230, 233.*
Mainka, C.; Prey, A.; Tams, E., s. (1258).
1037. Majorana, Q. PM 6 **39,** 488/504, 1920. *9.*
1038. Makover, W. Mesures pratiques en radioactivité, Paris 1919. *108.*

———; Geiger, H., s. (523).
Mallet, R.
1039. TrS **21,** 50/106, 1848. *204.*
1040. Treatise of earthquake phenomena, London 1859; Deutsche Bearbg. v. H. Jeitteles, Progr. d. k. u. k. kath. Staats-Gymnas., Kaschau 1860. *207.*
1041. BR 1861, 201/36. *207, 246.*
1042. Mandelslohe, Graf Fr. v. NM **15,** 440/3, 1844. *278.*
1043. Marchand, E. AMé **55,** 183/4; Annuaire soc. mét. de France 183/6, 1907. *149.*
———; Brunhes, B., s. (262).
1044. Marconi. EW **59,** 877 ff, 1912, Ref.; JT **6,** 163, 1913. *201.*
1045. Marianini. SJ **49,** 22/53, 1827. *156.*
1046. Marineleitung. Hansa 1923, 28; AH 1923, 222. *201.*
1047. Marten, W.; Kähler, K. VM **256,** 119/32, 1913. *20, 129.*
Martin, L.; Tarr, R. S., s. (1519).
1047*a*. Martonne, E. de. Bul. Etudes hist. sci. de l'A.O.F. Gorée 1925 (41 pp.) *73.*
Mascart, E. E. N.
1048. CR **95,** 631/3, 1882; Jph **2,** 341/9, 1883. *14.*
1049. ABM 1890 B, 113/128, Paris 1892; Traité de Magnétisme. Paris 1900. (441 pp.). *80.*
Mathias, E.
1050. MT **9,** 1897 (29 pp.). *98.*
1051. CR **137,** 916/8, 1903. *72.*
1051*a*. CR **139,** 274/6, 1904. *72.*
1052. RG **20,** 482/95, 1909. *97.*
1053. Aph **18,** 83/170, 1922. *121.*
1054. Traité d'électricité atmosphérique et tellurique, Paris 1924 (580 pp.). *120, 130, 148, 154, 201, 202.*
1055. Matsubara, Atsushi. Mem. College of Science, Imp. Univ. Kyôto, Ser. B **1,** 285/332, 1924. *157.*
1056. Matteucci. CR **16,** 937/8, 1843; **19,** 114, 1844. *282.*
1056*a*. Matzusawa, T. JJA **3,** 161/77, 1926. *222.*
Mauchly, S. J.
1057. TM **29,** 187/94, 1924: PR 2 **25,** 254, 1925. *129.*
1057*a*. Sc. **21,** 641/5, 1925; Carnegie Inst. Publ. **175,** V. 385/424, 1926. *122.*
1057*b*. BRC **10,** 58, 1925. *122.*
1057*c*. Ann. Rep. Carnegie Inst. **227,** 1926. *121.*
1057*d*. Maurer, R. ZBB **34,** 371, 1926. *126.*
1058. Maurin, Ch. CR **176,** 847/50, 1923; **178,** 508/10, 1924. **182,** 647/9, 1926. *101.*
———; Eblé, L.
1059. CR **179,** 337/9, 1924. *233.*
1059*a*. CR **181,** 1077/8, 1925. *259.*
1060. ———; ———; Labrouste, H. Jph 6 **6,** 14/5, 65/78, 1926. *258.*
———; Madinhac, Mme. de
1061. CR **175,** 1046/7, 1922. APG **2,** 96, 1926. *151.*

1062. CR **176,** 1726/9, 1923. *67.*
1062*a*. Maurin, Ch; Salles, E.; Gibault, G. CR **180,** 1955/7, 1925. *150.*
Maurer, J.
1063. MZ **28,** 77/80, 1911. *273.*
1064. AG **36,** 5/12; MZ **30,** 407/10, 1913. *106.*
1065. Maydell. Morskoj Sbornik, 1883, No. 3. *100.*
1066. Mayr, Otto. ETZ **46,** 1352/5, 1436/40, 1925. Arch. f. Elektrotechn. **16,** 303, 1926. *172.*
1067. Mazelle, E. MW **15,** Wien 1903 (87 pp.). *227.*
1067*a*. Meier, O. ZS. Oesterr. Ing. Ver. **77,** 217/21, 1925. ZO 1925, 675/85. IZBE **34,** 39/40; AÖCh **44,** 105/6, 117/23, 1926. *176, 180, 191.*
1068. Meinesz, N. Publ. de la commission géodésique Néerlandaise. Ref. Na. **13,** 535, 1925. *15.*
1069. Meisser, O. ZG **1,** 32/5, 1924/5. *52.*
Meisser, O.; Martin
1069*a*. ZG **2,** 269/71, 1926. *240.*
1069*b*. ZG **3,** 106/18, 1927. *249, 250, 261.*
Meissner, A.
1070. ZtP **2,** 328/30, 1921. *200.*
1071. JT **24,** 85/92; El. Masch. **42,** 625/30, 1924. *201.*
———, E.
1072. VZ **66,** 181/95, 1921; **67,** 1/8, 1922. *222, 225.*
1073. VZ **69,** 34 ff, 1924. *258.*
———, O.
1074. Seismometr. Beob. in Potsdam 1913. *223.*
1075. BG **13,** 204/9, 1914; Na **6,** 52/5; AH **46,** 85/92, 183/90, 1918; **48,** 169/76, 1920. *227.*
1076. Seismometr. Beob. in Potsdam 1914. *224.*
1077. BG **14,** kl. Mitt. 1/7, 1915. *223.*
1077*a*. AN **207,** 273/82, 1918. *38.*
1077*b*. PZ **21,** 443/4, 1920. *211.*
1078. AN **206,** 25/44, 1917; **214,** 201/12, 1921. *41.*
1078*a*. ZV 1922, Heft 9; 1925 Heft 7/8, *38.*
1079. Meli, Rom. Boll. della Soc. Geologica Italiana **3,** 645/70, 1890. Roma 1891. *96.*
Melkus; Gorjanović-Kramberger; Steeb, s. (572).
1080. Melloni, M. Atti del Accad. Pont. d. Nuovi Lincei **5,** 666/85, Roma 1851/2; Memorie della R. Acad. dell Science **1,** 121/64, Napoli 1852/4; Sulla polarità delle lave e roccie affini, Neapel 1856. *95, 96.*
1081. Melmer, Rud. WB **120,** 269/81, 1911. *269.*
1082. Mercalli. BSJ **8,** 181/91, 1902/3. *216.*
Mercanton, P.-L.
1083. AG **23,** 467/82, 1907; CR **166,** 681/2, 949, 1918; *96.*
1084. CR **151,** 1092/4, 1910; **165,** 632/4, 1917; **174,** 1117/8, 1922; **182,** 856/60, 1231/2, 1926; AG 4 **44** 359/61, 1917. TM **31,** 187/90, 1926. *95.*
1085. AG **121,** 496/501, 1916. *130.*
1086. Jph 6 **4,** 250/1, 1925. *96.*

1087. Merian, P. AP 2 **48,** 383/4, 1839. *266.*
1087*a*. Merryman, W. W. PR 2 **27,** 659/71. 1926. *122.*
1087*b*. Merten, E. Diss. Freiburg 1924 (unpublished). *260.*
1088. Meslin, George. CR **141,** 1006/8, 1905. *95.*
1089. Mesny, R. OE **1,** No. 10/11, 1922; **2,** No. 17, 1923. *201.*
Messerschmitt, J. B.
1090. JZ **6,** 15/40, 1892. *46, 357.*
1091. JZ **6,** 9/14, 1892. *72.*
1092. ZV **28,** 634/8, 1899. *59.*
1093. MB **35,** 135/68, 1905. *97.*
1094. Die Schwerebestimmung an der Erdoberfläche. (Die Wissenschaft 27). Braunschweig 1908. *11, 19, 29, 40.*
1095. Meyen. Magnetische und meteorologische Beobachtungen am physikalischen Haupt-Institut, Petersburg 1852. *100.*
1096. Meyer, G. BF **12,** 134/74, 1902. *99.*
1097. ———, H. Diss. Göttingen 1880; AP 3 **19,** 70/2, 1883. *74, 140.*
1098. ———, Osk. Em. JSch **66,** 49/58, 1888; NR **4,** 465/6, 1889; JSch **69,** 49/50, 1891. *72, 74, 99.*
———, Stephan
1099. PZ **10,** 860/2; ZJ **29,** 65/8, 1909. *117.*
1099*a*. Die radioaktiven Substanzen. Handbuch der Biolog. Arbeitsmethoden. Abt. II. Phys. Math. Tl. 2, Heft 5. pp. 1537/1643, 1926. *107.*
———; ———; Jäger, G., s. (758).
———; Mache, H., s. (1015), (1016).
———; ———; Schweidler, E. R. v., s. (1017).
1100. ———; Schweidler, E. R. v. Radioaktivität, Leipzig-Berlin 1916. (541 pp.). *107, 115, 116, 117, 121.*
1101. Mezger, C. Gl **53,** 689, 721, 1917. *279.*
1102. Michelson, A. A.; Gale, H. G. AphJ **50,** PR 2 **15,** 144, 1920. *36.*
1103. Middlemiss, C. S. Rec. Geol. Survey of India **32,** 4, Calcutta 1905. *31.*
1104. Mielberg, J. RM **10,** No. 1 (38 pp.), 1885. *79.*
1105. Milch, L. GR **2,** 145/62, 1911. *36.*
1105*a*. Millikan, R. A. NL **116,** 823/5, 1925; Sc. **134,** 149/50; AP 4 **79,** 572/82; Pr. W **12,** 48/55, 1926. *122.*
1105*b*. ———; Bowen, I. S. PR 2 **27,** 353/61, 1926. *122.*
1105*c*. ———; Otis, R. M. PR 2 **23,** 778/9, 1924; **27,** 645/58, 1926. *122.*
Milne, John
1106. TrSJ **8,** 1/82, 1885. *155, 207, 242, 246, 260.*
1107. TrSJ **11,** 1/78, 1887. *225.*
1108. TrSJ **12,** 67/75, 1888. *265.*
1109. TrSJ **15,** 135/61, 1890; SJJ **3,** 23/36, 1894. *155.*
1110. BR 1891, 583. *149, 155.*
1111. NL **45,** 127, 1892. *265.*
1112. SJJ **17,** 87/112, 1893. *225.*
1113. TrM **5,** 203/18, 1893; SJJ **19,** 65/9, 1894. *265.*
1114. NL **67,** 538/9; EbW **3,** 6/10, 1903. *211, 212, 234.*
1115. Milne, John; Gray. PrS **33,** 139/40; PT **173,** 863/83, 1882. *246.*

Mintrop, L.
1116. Diss. Göttingen 1911. *226.*
1117. Gl **50,** 330/9, 1914. *265.*
1118. DRP 304317 (17. 5. 17). *247.*
1119. DRP 303344 (25. 5. 17); 303345 (3. 8. 17). *236, 237.*
1120. DRP 371963 (7. 12. 19); 417010 (1. 11. 20); 386909 (31. 8. 21); Gl **56,** 752, 1920. *248, 249, 250.*
1121. Mischpeter. SK **27,** 9/32c, 1887; **28,** 1/26, 1888; **29,** 1/26, 1889; **30,** 1/26, 1890; **31,** 33/58; 1891; **34,** 62/76, 1893. *272.*
1121*a*. Mitchell, A. C. PrE **45,** 297/301, 1925. *67.*
Mitkewitch, V; Loewinson-Lessing, F., s. (977).
1122. Mohn, H. VK **1,** No. 2, 1899 (69 pp.). *16.*
Mohorovičić, A.
1123. Jahrb. d. meteorolog. Observ. Agram 1909. *221, 259.*
1124. BAA **15,** Rad. **226,** 1922; Publ. Bur. Centr. Séismol. Int. (A) **3** (56 pp.), Paris 1925. *211.*
1125. BS **14,** 38 ff., 1924. *230.*
1125*a*. BG **15,** 201/14, 1926. *233.*
1126. ———; Mohorovičić, Stj. BAA, Rad. **226,** 94/190, 1921. *211.*
1127. ———, Stj. BG **13,** 217/40, 1914. *220, 259.*
1128. BG **14,** 199/205, 1916. *212, 218.*
1129. AN **220,** 245/50, 1924; ZaG **1,** 330/83, 1924/5. *211, 221, 267.*
1130. Molisch, Hans. WB **121,** 833/57, 1912; Na **2,** 104/6, 1914. *128.*
1131. Moll, H. MML **33,** 1922; Ste **21,** Heft 20, 1922; **22,** Heft 1 and 2 1923; Bu **16,** 125/8, 149/53, 176/9, 1923. *100, 105.*
1132. Molla, P. J. Garcia. Mém. Observ. de l'Ebro, No. **4,** 95/119, Barcelona 1910. *148.*
Möller
1132*a*. ME **23,** 351/3, 1926. *104.*
1132*b*. ME **23,** 299/301, 1926. *191.*
Montessus de Ballore, F. de
1133. BG **4,** 331/82, 1900; **6,** 21/41, 1904; BG Erg. Bd. **2,** 325/34, 1904; Les tremblements de terre. Geographie séismologique. Paris 1906; CR **158,** 440/1, 1914; La géologie sismologique. Les tremblements de terre, Paris 1924. (488 pp.). *219.*
1134. L'Architecture **19,** 335/44, Paris 1906. *265.*
1135. Historia sismica de los Andes meridionales, Santiago de Chile. *220.*
1136. Monti, V. RL **16,** 916/20, 1907. *224.*
1136*a*. Moore; Ebutt: MgM **35,** 307/9; CI **47,** 931/3, 1926. *190.*
1136*b*. Morley, D. A. GJ **51,** 175/82, 1918. *42.*
1137. Mortenson. KB **5,** 209/13, 1925. **6,** 77/80, 1926. *189, 191.*
1137*a*. Mothes, H. GR **17,** 397/400, 1926. *210, 257, 263.*
Moureaux, C. Th.
1138. ABM 1890, B 95/112; CR **137,** 918/20, 1903; ABM 1904, 24/82; AMé **55,** 188/95, 1907. *101.*
1139. ABM **4,** 25/38, 1896. *148.*
1140. CR **122,** 1478, 1896; Mém. de la Soc. Imp. Russe de Géograph., Sect. de Geogr. Génerale **32,** No. 3, Pétersbourg 1898; AMé **46,** 14/5, 1898. *103.*

1140*a*. Moureu, Charles; Lepape, Adolphe. CR **158,** 598/603, 1914. *131.*
1140*b*. Moyle, M. P. TrC **2,** 404/15; Jph **95,** 307/14; TA 3, 308/10, 415/6, 1822. *266, 267.*
1140*c*. Mueser. AOCh **34,** 134/5, 1926. *169, 186.*
Mügge, O.
1141. ZM 1909, 65/71, 113/20, 142/8. *73, 124.*
1142. GN 1921, 217/22. *277.*
1143. GN 1923, 1/16; ZK **59,** 437/41, 1924. *124.*
Mühlberg, M.; Koenigsberger, J., s. (842).
1144. Müller, C. H.; Timpe, A. Die Grundgleichungen der mathematischen Elastizitätstheorie. EM IV, **4,** 1/54, 1908. *207.*
1145. ———, J. ZaC **37,** 201/2, 1924. *133.*
1146. ———, J. J. A. NL **113,** 308/9, 1924. **117,** 786, 1926. *15.*
1147. ———, P. A. BAP **30,** No. 4, 531/62, 1886; Mélanges Phys. Chim. Acad. St. Pétersbourg, **12** 4, 431 ff., 1886. *146.*
1148. ———Pouillet. Lehrbuch der Physik und Meteorologie, IV. Bd. Braunschweig 1909/14. *61, 64, 66, 68, 70, 74, 80, 81, 84, 85, 88, 91, 108, 120, 147, 149, 153, 237.*
1148*a*. Müller, M. ZG **2,** 287/91, 1926. Gl **63,** 41/50, 1927. *171, 357.*
1148*b*. Müns, R. Diss. Kiel 1913. *122.*
1149. Munthe, C. Die innere Wärmeleitungsfähigkeit von Bodenarten bei verschiedenem Feuchtigkeitsgehalt, Upsala 1915 (79 pp.). *268.*
1149*a*. Muschketoff. BJP **1,** 7/17, 1925. *357.*
1150. Müttrich. Beobachtungen der Erdtemperatur auf den forstlichen meteorologischen Stationen in Preussen, Braunschweig und Elsass-Lothringen. Berlin 1880. *272.*
1150*a*. Myssowsky, L.; Tuwim, L. ZP **39,** 146/50, 1926. *123.*

1151. Nagaoka, H. PEJ **4,** Tokyo 1900. *207.*
———; Tanakadate, A., s. (1517).
1151*a*. Nakamura, S. Proc. Phys. Math. Soc. Japan **3,** 127/30, 1925. *226.*
1151*b*. Nakano, Hiroshi. JJA **2,** 233/326; **3,** No. 5, Tokyo; Contr. Centr. Met. Obs. Japan **1,** 1/94, 1925 (Ref. ZG, **1,** 374/7, 1925). *206.*
1152. Nathorst, H. TT **49,** 42/6, 1919; **50,** 73/4, 1920; **51,** 128/30, 1921; **52,** 96, 1922. *161, 186.*
Naumann, E.
1153. Die Erscheinungen des Erdmagnetismus in ihrer Abhängigkeit vom Bau der Erdrinde, Stuttgart 1887. *70, 74, 87, 97, 102.*
1154. GM 3 **6,** 486/90, 535, 44, 1889; ZWG **7,** 493/506, 1890. *87, 97.*
1155. ZDG **51 C,** 114, 1899. *104.*
Navarro-Neumann, Ma. S.
1156. Bosquejo sismico de la Peninsula Ibérica. Granada 1921. *220.*
1157. Jb No. 533, 1924 (5 pp.); No. 572, 1925 (8 pp.). *240.*
1157*a* Negro, C. Elettricità atmosferica, Milano 1926. (299. pp.) *120.*
1158. Nernst, W. Lehrbuch der theoretischen Chemie. 7. Aufl. Stuttgart 1913. *145, 147, 149.*
Nerville, de. *199.* S. a. (886).
1159. Nesper, Eugen. Handbuch der drahtlosen Telegraphie und Telephonie, Berlin 1921. *193.*

1160. Neuburger, M. C. Sammlung chemischer und chemisch-technischer Vorträge **26,** 229/38, Stuttgart 1922. (Viel Lit.) *110.*
1161. Neumayer, G. von. MZ, Hann-Bd., 67/80, 1906. *97.*
1163. Nichols, H. W.; Schelleng, J. C. NL **115,** 334; Sc **61,** 288/90; Bell system Techn. Journ. **4,** 215/34, 1925. *200.*
1164. Niemczyck, O. Gl **59,** 929/36, 953/7, 972/8, 1923. *33.*
Niethammer, G.
1165. EH **11,** 96/120, 1910. *38, 273.*
1165*a*. Verhdl. Schweiz. Naturf. Ges. **91,** 43/62, 1908; ibid. 1921. *274.*
Nikiforov, P.
1166. Bull. de l'Instit. Physico-math. de l'Acad. d. Sci. de Russie, Petrograd I, 1, 1922 (57 pp.) *58.*
1167. CRS **7** 3, 343, 382 ff., 1924; BJP **1,** 153/257, 1925. *20.*
1168. Nilson. AP 2 **42,** 472/6, 1837. *33.*
1169. Nipher, F. Chart of the magnetic variation in Missouri, St. Louis 1880. *102.*
Nippoldt, A.
1170. MZ **21,** 393/9, 1904. *68.*
1171. PZ **7,** 242/8, 1906. *66.*
1172. MZ **25,** 97/103, 1908. *66.*
1173. BG **10** 2, 150/6, 1910. *73.*
1174. MZ **28,** 244/61, 1911. *152, 154.*
1175. Na **3,** 349/52, 1915. *73, 98.*
1175*a*. VM, Tätigkeitsber. 1917/9, 90/100, Berlin 1910. *99.*
1176. Ste **16,** 157, 1921. *72, 88, 105.*
1177. Erdmagnetismus, Erdstrom und Polarlicht (Sammlung Göschen 175) 3. Aufl. 1920. *69, 70, 72, 151, 154.*
1177*a*. Weltall **24,** Heft 5. *70.*
1178. ZFP **1,** 181/3, 1922. *75.*
1179. Na **11,** 37/41, 1923; PG **70,** 84, 1924. *71, 73.*
1180. GA **3,** 114/37, 1924. *99.*
1181. Na **12,** 351/2, 1924. *100, 153.*
Nippoldt, A.; Schering, K., s. (1360).
1182. Niven, C. PrS **76,** 34/48, 1905. *269.*
Noguès, A. F.
1183. CR **106,** 1110/2, 1888. *207, 242, 246.*
1184. CR **109,** 54/7, 1889. *219.*
1185. Nölke, F. Geotektonische Hypothesen, Berlin 1924. (Geophysikal. Schriften **2**); GR **15,** 300/5, 1924. *32.*
1186. Nordmann, Ch. CR **146,** 1357/8, 1908. *101.*
1187. Norton, F. N. JFr. **198,** 231/42, 1924. *239, 242.*
1188. ———; Warner, E. P. Accelerometer design. Nat. Advisory Comm. f. aeronautics Rep. 100. *242.*
1188*a*. Numerov, B. ZG **1,** 367/71, 1925. *48.*

1188*b*. Obata, H. JJA **2,** 141, 1925. *265.*
Oberguggenberger, V.
1189. PZ **25,** 682/4, 1924. *150.*
1190. WB **132,** 59/68, 1923. *130.*

1190*a*. Oberste-Brink, K. MM 1914, 69; Gl **62,** 857/68, 1926. *33.*
1190*b*. Obolensky. AP 4 **77,** 644/66, 1925. *121.*
1190*c*. Ockendon, C. V. Meteor. Mag. London **69,** 220/1, 1924. *122.*
1191. Oddone, E. RL **19,** 648/56, 1910; VS **4,** 237/47, 1911. *207.*
1192. ———; Franchi, S. AR **12** 1, 133/49, 1890, Roma 1893. *96.*
1193. ———; Sella, V. RL 4 **7** 1, 100/4, 148, 1891. *96.*
1194. Odelsió, H. Kgl. Sjökarteverket, Jordmagn. Publ. No. 3, Stockholm 1924. *100.*
Oldham, R. D.
1195. Mem. geolog. Survey of India No. 29, Calcutta 1899. *31, 215.*
1196. PrS **90,** 32/41, 1914. *59.*
1196*a*. Mem. geolog. Survey of India **42,** pt 2, 1917. *42.*
1196*b*. PM 7 **1,** 896, 1926. *220.*
1196*c*. Ollendorff, Franz. Die Grundlagen der Hochfrequenztechnik, Berlin 1926 (655 pp.). *193, 200.*
Omori, F.
1197. PEJ No. **4,** Tokyo 1900; VS 1901; BG Erg.-Bd. **1,** 335/401, 1902. *245, 265.*
1198. PEJ No. **5,** 1/82, 1901; No. **13,** 59 ff., 1903; No. **21,** 9/102, 1905; No. **23,** 1/16, 1907; No. **24,** 1/273, 1907. *224.*
1199. PEJ No. **21,** 1905; BEJ **1,** 167/171, 1907. *227.*
1200. BEJ **2,** 1/6, 1908. *228.*
1201. VS **4,** 254/61, 1911; BEJ **8,** No. 2, 35/179, 1916. *32, 226.*
1202. BEJ **5,** No. 1, 1911; No. 3; 1913; **9,** No. 2, 1920; VS **4,** 248/53, 1911. *32, 234.*
1202*a*. Ono, S. JJA **3,** 11/37, 1925. *63.*
1203. Oppolzer, Th. von. ZJ **4,** 303/16, 379/87. 1884. *14.*
1203*a*. Orlow, J. A. BAP 6 **4** 1, 775/85, 1910; Diss. Dorpat 1911. *36.*
Orstrand, C. E. van
1204. West Virginia Geolog. Survey, County Rep. 1918, 1/79; EG **19,** 229/48, 1924. *277.*
1204*a*. EG **21,** 145/65, 1926. *282.*
1205. Ossat, G. de A. d'. RL 4 **12,** 278/84, 1903. *140.*
1206. Ostermeier, J. B. ZBB **33,** 144/7, 158/60. 1925. ZtPZ **7,** 196/8, 1926, 99. *126, 357.*
1206*a*. AÖCh **44,** 113, 1926. *191.*
1206*b*. IZBE **34,** 24/33; AÖCh **44,** 93/101, 1926. *357.*
Owen; Briggs; Wilson, s. (245a).
1206*c*. Pacini, D. RL 6 **1,** 713/6, 1925. *151.*
Pal, G.; Watson, H. E., s. (1583).
Palazzo, Luigi
1207. RL 4 **7,** 615/23, 1891. *101.*
1208. RL 5 **32,** 208/14, 1923. *101.*
1208*a*. RL 5 **33,** 452 ff., 1925. *74.*
1208*b*. IGU **6,** 21/29, 1926. *96.*
1209. Palmieri, L. NaR **28,** 250/3, 1889; LE **38,** 51/3, 1890; NaR 6, No. 12, 1/10, 1894; EEl **2,** 577/82, 1895; NaR **7** (2a), No. 6, 1/7, 1895; EEl **7,** 442/6, 1896; NaR **8,** No. 4, 1/6, 1897. *150.*

1209*a*. Pardo. Rev. Min. **77,** 1926. *357.*
1210. Pascal, P. CR **175,** 814/6, 1922. *95.*
1211. Pascoe, E. H. Mem. Geolog. Surv. of India **40** 1, Calcutta 1912. *282.*
Passalskij P. T.
1212. Bull. Imp. Univ. de Odessa **85,** 1/547, 1900. *72, 103, 106.*
1213. Anomalies magnétiques dans la région des mines de Krivoi-Rog., Odessa 1901; Ref. by Hazard, TM **7,** 46/7, 1902, s. (652). *72, 87, 103, 106.*
1214. Paulsen, A. Kgl. Danske Videnskabernes Selskabs, Forhandlinger 1896, 246/86. *74, 87, 100.*
1215. Pautsch, E. Diss. Hamburg 1922. (Ref. ZaG **1,** 57, 1923.) *219.*
1216. Pechau, W. BG **13,** 206/16, 261/82, 1914. *222, 223.*
Pekár, Des.
1217. Na **7,** 327/31, 1919. *8.*
1218. Na **7,** 149/59, 1919. *20.*
1219. ZJ **42,** 173/8, 1922; **43,** 187/95, 1923. **45,** 486/93, 1925. *20, 24.*
———; Eötvös, R. v.; Fekete, E., s. (403).
Penkava, Jos.; Stoklasa, Jules, s. (1487).
1219*a*. Penkewitch, M. S. Journ. Geoph. Met. Leningrad **2,** 217/22, 1925. *72.*
Pentscheff, P.; Bachmetjew, P., s. (84).
1220. Perot, A. CR **175,** 869/72, 1922; Jph **179,** 151/2, 1922. *14.*
1221. Perrot. CR **54,** 728/9, 851/2, 1862. *86.*
Peters, W. J.
1222. TM **28,** 83/8, 1923. *151.*
1222*a*. IWA **16,** 373, 1926. *40, 154.*
———; Bauer, L. A., s. (132), (133).
1222*b*. ———; Ennis. TM **31,** 57/70, 1926. *154.*
1223. Petersen, J. Danish Biolog. Stat. Rep. **3,** 31/2, 1893. *281.*
1224. Petersson, W. JA **62,** 151/71, 1907; Gl **43,** 906/10, 1907. *167.*
1225. Petherick, Thomas. PM 3 **3,** 16/7, 1833. *156.*
1226. Petrascheck, W. VGW 1915, 45/66. *123.*
———; Schumann, R., s. (1409b).
Petrowskij, A.
1226*a*. BJP **1,** 87/106, 1925. *158.*
1226*b*. BJP **1,** 107/35, 1925. *146, 160, 162.*
1226*c*. BIP **1,** 73/85, 1925. *144.*
1227. Peust, Alb. DRP 168 248 (3. 6. 05) †. *168.*
Pfaff, F. W.
1228. ZDG **42,** 303/17, 1890; **51,** 125/50, 1899. *14.*
1229. GJM **21,** 219/26, 1908. *98, 106.*
1230. GJM **26,** 187/233, 1913. *92, 98, 106.*
1231. BG **13,** 182/204, 1914. *15.*
1232. ZpG **33,** 41/52, 1925. *98, 105.*
1233. Pfalz, Rich. Ge No. **37,** 810/15, 1925. *200.*
Phemister, T. C.; Johannsen, Alb., s. (771).
1234. Phillips, John. BR 1836, 291/3, *276.*
———; Hunt, Rob., s. (753).

———, P.; Poynting, J. H., s. (1251).
1235. Piccard, Auguste. Jph 6 **6,** 17/8, 1925. *233.*
———; Quervain, A. de, s. (1263).
1236. Pickard, G. W. PrR **10,** 161/175, 1922. *201.*
Piepmeyer, W.
1237. DRP 408 819. *161.*
1238. DRP 415 188 (11. 1. 23). *164, 182.*
1239. Piltschikoff. Jph 2 **7,** 437/9, 1888. *66, 74.*
Platiana, Giovanni; Gaetano, s. (494).
1240. Pochettino. Ciel et Terre, Bruxelles **39,** 34/6, 1923. *72.*
Pockels, F.
1241. NM 1897 1, 66/73. *96.*
1242. PZ **2,** 306/7, 1901; **3,** 22/3, 1902. *96.*
1242*a*. Pödder. TM **31,** 103/8, 108/12, 1926. *68.*
Poggendorf, J. L.
1243. Okens Isis 1821, 687/710 (p. 706). *156.*
1244. AP 2 **13,** 363/76, 1828. *273.*
1245. Polescjuk. CRS **4,** Lfg. 1, VIII/XII, 1911. *265.*
1245*a*. Pollaczek, F. EN **3,** 339/59, 1926. *172.*
Pollock, J. A.; Threlfall, R., s. (1537).
1246. Poole, Horace H. PM 6 **24,** 45/62, 1912; **27,** 58/83, 1914. *271.*
1247. ———, J. H. J. PM 6 **40,** 466/71, 1920. *125.*
1248. ———; Joly, J. PM 6 **48,** 819/32, 1924. *124.*
1249. Poppendieck, R. Diss. Darmstadt 1911. *79.*
1250. Potter, Harold H. PR 2 **19,** 187/8, 1922. *9.*
1251. Poynting, J. H.; Phillips, P. PrS **76,** 445/57, 1905. *9.*
Pratt, J. H.
1252. On the variation of gravity at Kaliana, Kalianpoor and Damargida; produced by the irregularities of the earth's crust, Dehra Dún 1869. *46.*
1253. PT **161,** 335/57, 1871. *37.*
1254. Pressel, K. MB 1912, 93/6. *274.*
1255. Prestwich, Jos. PrS **38,** 161/8, 1885; **41,** 1/116, 1887. *266, 268, 273, 282.*
Prey, A.
1256. WB **121** 2, 2467/518, 1912; **123,** 875/902, 1914. *11, 38, 42.*
1257. Na **12,** 312, 1924. *16.*
1257*a*. Die Theorie der Isostasie. Berlin 1925. (242 pp.) *38.*
1258. ———; Mainka, C.; Tams, E. Einführung in die Geophysik, Berlin 1922. *16, 26, 29, 32, 36, 38, 40, 46, 216, 220, 230, 233, 236.*
1258*a*. Puig. Ib **13,** 198/202, 215/7, 1926. *148.*
Pusch, J.; Abraham, M.; Traubenberg, H. Rausch v., s. (5).
1258*b*. Putnam, G. R. CS 1894 App. 1; Bull. Washingt. Phil. Soc. **13,** 61 ff. 1894. *38.*
1258*c*. Quayle, Ph. P. BRC **11,** 53/4, 1926. *16.*
Quervain, A. de
1259. BG **13,** 148/62, 1913. *220.*

1260. JSE 1913, Anh. S. 12/17; Ann. d. Schweiz. Meteorol. Zentr.-Anst. 1913, Zürich 1915. *221.*
1261. JSE 1921, S. 7/10. *259.*
1262. JSE 1922, Anhang, Zürich 1923. *233.*
1262*a*. BG **15,** 317/20; ISE 1924, 1926. *221.*
1263. ———; Piccard, A. Verhandlungen d. Schweiz. Naturf.-Ges., Bern 1922 2, 186/7; AG 1923. ISE 1924, 12/21, *233.*
Quincke, G.
1264. AP 2 **107,** 1/47, 1859; **110,** 38/65, 1860; PM **19,** 455/8, 1860; ACh **57,** 379/84, 1859; **59,** 494/8, 1860. *152.*
1265. AP 3 **24,** 347/416, 606/18, 1885. *91.*
Quiring, H.
1266. Gl **59,** 405/10, 1923. *57.*
1267. Gl **60,** 807/11, 1924; ZBB **33,** 6, 1925. *58.*
1267*a*. DRP 429 034 (29. 4. 26) *28.*
1268. Quittner, V. Diss. Zürich; AG **26,** 358/93, 455/501, 585/608, 1908. *90.*

1268*a*. Raclot. CR **164,** 150/1, 1917. *74.*
1269. Radium. Abgabe von, Normallösungen durch die Physikalisch-Technische Reichsanstalt. PZ **24,** 286/7, 1923. *118.*
1269*a*. Ramsauer, C. AP 4 **75,** 449/58, 1924. **80,** 436, 1926. *150, 151.*
Ramsay, R. R.
1270. PM 6 **30,** 815/8, 1915. *131.*
1271. Bull. Commiss. Geol. de Finlande No. 66, 1924. *33.*
Rawen, Ed.
1272. DRP 331426 (5. 4. 19);† 331427 (6. 4. 19).† *196.*
1273. DRP 334626 (4. 4. 19)† *179.*
1274. DRP 344489 (5. 7. 19).† *76.*
Ray, S.
1274*a*. ZP **33,** 48, 1925. *150.*
Rayleigh, Lord
1275. PrL **17,** 4/11, 1887. *206.*
1275*a*. PrS **77,** 475, 1906. *133.*
1276. Rebeur-Paschwitz, E. v. BG **2,** 211/536, 1895. *225, 234.*
1277. Redenbacher, W. Diss. München 1917; Zs. f. d. ges. Kälteindustrie **25,** 71/4, 79/82, 1918. *268.*
1278. Reeh, Reinh. DRP 398311 (8. 12. 21); 399 179 (11. 1. 22). *242.*
1278*a*. Rees. JCT **113,** 688/9, 1926. *282.*
Regelmann, C.
1279. JW 1907, 110/76. *219.*
1280. JOG **40,** 11/17, 1907. *33.*
Reich, F.
1281. Beobachtungen der Temperatur des Gesteins in verschiedenen Tiefen in den Gruben des sächsischen Erzgebirges. Freiberg 1834. *266.*
1282. AP 2 **48,** 287/91, 1839; EJ **28,** 1/15, 1840; BR 1839 2 34/5; Karstens Archiv **14,** 141/58, 1840. *156.*
1283. BH **3,** 342/6, 386/90, 1844. *156.*
1284. LB **2,** 237/47, 1848; AP 2, 32/43, 1849. *96.*

———, H.
1285. JGB **42,** 697/722, 1921. *217.*
1286. GN 1921, 93/8. *35, 217.*
1287. SE **41,** 547/8, 1921; ZG **1,** 120/1, 1925. *223, 250, 357.*
1288. JGB 1923, 319/42 (1923). *105.*
1289. Pumpen-, Brunnenbau, Bohrtechnik **21,** 151/5, 191/3, 227/31, 263/7, 1925. *179, 250, 357.*
1289*a*. Elektr. i. Bergbau **1,** 10/1, 1926. *104.*
1289*b*. IGB **46,** 249/91, 1925. *200.*
1289*c*. IGB **47,** 84/115; Za C **39,** 1215; ZG **2,** 272/7, 1926. *104.*
1289*d*. Pumpen, Brunnenbau **22,** 221/3, 1926. *191.*
1289*e*. ME **23,** 281/8, 1926. *357.*
———, M.
1289*f*. JT **5,** 176/88, 253/61, 1912. *200, 201.*
1289*g*. PZ **14,** 934/8, 1913. *200.*
1290. ———; Fischer, F. ZP **32,** 327/32, 1925. *172.*
Reichenheim, O.; Koenigsberger, J., s. (843).
Reichsanstalt; Abgabe von Radium-Normallösungen durch die Physikalisch-Technische, s. (1269).
Reid, H. F.
1291. Rep. of the State Earthquake Invest. Comm. **2,** 55, Washington 1910. *217.*
1291*a*. BS **15,** 222/41, 1925. *233.*
1291*b*. Reinhold. Polytechn. Weekblad **20,** 728/9, 1926. *357.*
1292. Riccó, A. Catania, Bull. Accad. Gioenia **80,** Febr. 1904; AR **19,** AH. 1897; 19. 1. 1907 (10 pp.); CT **29,** 153/63, 205/12, 1908; BSJ **12,** 1908. *42, 88, 101.*
1292*a*. Richards, Th. W., Hall, L. P. Journ. Amer. Chem. Soc. **48,** 704/8, 1926. *132.*
Richarz, Fr.; Krigar-Menzel, Otto.
1293. BB 1893 1, 163/83. *20.*
1294. BB 1896 2, 1305/18. *20.*
1295. Rikatscheff, M. RM **1,** 201/52, 1869/70. *84.*
1295*a*. Riley, W. C. Engg **118,** 733/4, 1924. *170.*
1295*b*. Rodebush, W. H.; Fiock, E. F. PrW **11,** 402/4, 1925. *150.*
1296. Rodés, S. TM **27,** 161/6, 1922. *67.*
1296*a*. Rogers. CJ **157,** 1153/6, 1926. *189.*
1297. Rolland, P. le. Aph 9, **17,** 165/381, 1922. *12, 13.*
1298. Rooney, W. J.; Gish, O. H. PR 2, **25,** 254, TM **30,** 161/88, 1925. *141, 167.*
1299. Rösch, S. Na **12,** 868/77, 1924. *36, 212, 267.*
1299*a*. Rose, G. Karte der magnet. Deklination in Russland 1925. Leningrad. *73.*
1300. Rösener, F. Diss. Göttingen 1912; BG **12,** 207/76, 1913. *224.*
Rosenthal, E.
1301. VS **2,** Haag 1907. 257/60. *222.*
1302. BG **13,** 28/63, 1913. *220.*
1303. BG **12,** kl. Mitt. 52/55, 1913. *218.*
1304. Roth, W. Na **7,** 416, 1919. *8.*

Rothé, E.
1305. CR **172,** 1345/7, 1921; Aph 9, **17,** 385/415, 1922. *202.*
1306. CR **177,** 1050/3, 1923. *249.*
1306*a*. Le tremblement de terre. Paris 1926. (247 pp.) *207.*
1306*b*. ———; Lacoste, J.; Bois, Ch. CR **180,** 2053/4, 1925. *259.*
1307. CR **179,** 507/9, 1924. *258.*
———; Dammann; Hée.
1307*a*. CR **179,** 339/42, 1924. *238.*
1308. Rothpletz, A. MB 1910. 8. Abhdl. (32 pp.). *32.*
Royers; Lindberg, s. (1003).
Rücker, A. W.
1309. PrS **48,** 358, 505/35, 1891. *87, 92, 93, 94, 100, 101.*
1310. BR 1895, 633/4; PrP **14,** 85/93; PM **41,** 99/106, 1896. *151.*
1311. TM **1,** 105/46, 1896. *100.*
1311*a*. TM **4,** 113/29, 1899. *74.*
1312. PrP **17,** 609/18, 1901; Notices of the Proceed. of the Meetings of the Members of the R. Instit. of Gr. Britain **16,** 124 1902. *155.*
———; Thorpe, T. E.
1313. PT **181,** 53/328, 1890; **188,** 1/661, 1896. *73, 100, 101.*
1314. PrS **47,** 443/5, 1890. *100.*
1315. Rüdenberg, Reinh. ETZ **42,** 847/8, 1921; Wiss. Veröffentl. a.d. Siemens-Konzern **1,** 61/80, 1922; ETZ **46,** 1342/6; ZaMP **5,** 361/89, 1925; ETZ **47,** 322/4, 359/64, 1926; Elektrische Schaltvorgänge, Bln. 1926. *141, 172.*
1316. Rudge, W. A. Douglas. PrC **19,** 1/10, 1916; El **79,** 345/6, 1917. *121.*
Rudolph, E.
1317. BG **2,** 537/666, 1895 (pp. 609 f.). *216.*
1318. VS **3,** 21, 1909. *228.*
1319. C. R. Congr. Geol. Intern. 11. Sess. Stockholm 1910. Bd. **2,** 837/47. *219.*
———; Szirtes, S.
1320. BG **13,** MS 71/81; PG **59** 2, 182/5, 249/52, 1913. *218.*
1321. PG **60,** 124/30, 184/9, 1914. *219.*
1322. Na **2,** 865/71, 1914. *222.*
Rudzki, M. P.
1323. Anzeiger d. Akad. d. Wiss. Krakau 1898, 166/79; BG **4,** 47/58, 1900. *223.*
1324. BG **3,** 519/40, 1898; BAC 1899, 373/84. *207.*
1325. BG **6,** 138/55, 1903. *230.*
1326. Physik der Erde, Leipzig 1911 (584 pp.). *207.*
1327. BAC 1911 (A) 503/36. *207.*
1328. BAC 1912, IA, 47/58. *207.*
1328*a*. BAC Mai 1913. *207.*
1329. Rüetschi, G. JOG **2,** 108/20, 1912. *31.*
Rukop, H.; Zenneck, J., s. (1663).
1330. Runge, C. GN 1907, 211/29; 1911, 99/109. *129.*
———, H.
1331. ME **21,** 240/1, 1924. *190.*
1332. ZBB **33,** 53/4, 1925. *190.*

Ruska, J.; Hobbs, W. H., s. (725).
1322*a*. Russell, Al. NL **116,** 609, 1925. *202.*
1333. Rutherford, E. Radioaktive Substanzen und inre Strahlungen. Handbuch der Radiologie, Bd. II. (Marx.). Leipzig 1914. *107.*
———; Joly, J., s. (786).
1334. Rybár, Ste. EG **18,** 639/62, 1923. *58.*
1335. Ryschkewitch, Eug. ZE **29,** 474/8, 1923. *141.*

1335*a*. Salles, E. CR **181,** 802/3, 1925. *121.*
Salles, E.; Maurain, Ch.; Gibault, G., s. (1062a).
1336. Salomon, W. Grundzüge der Geologie. Allgemeine Geologie, I. Teil. Innere Dynamik. Stuttgart 1922. *357.*
1337. Salpeter, Jac. WA 1909, 369/70; WB **118,** 1163/71, 1909. *127.*
Sandberg, C. G. S.
1338. Geodynamische Probleme. Teil I. Isostasie und die ursächliche Einheit von Gebirgsbildung und Vulkanismus. Berlin 1924 *35.*
1339. Geodynamische Probleme. Teil II. A. Tektonik und Metamorphose, B. Die Widersprüche in der Kontraktionstheorie. Bln. 1924. *35.*
1340. Sanderson, James Cox. AJ 4 **32,** 169/84, 1911; PZ **13,** 142/51, 1912. *129.*
Sanford, Fern
1341. PR 2 **18,** 314/6, 1921; **19,** 547, 1922. *152, 153.*
1342. Sc **57,** 616/8, 1923. *153.*
1343. Sc **59,** 194/6, 1924. *150.*
1344. Sano, S. PZ **4,** 8, 1903. *95.*
Satterly, John
1345. PM 6 **16,** 584/615, 1908. *120.*
1346. PrC **16,** 336/55, 1911. *128.*
1347. PrC **16,** 360/9, 1912. *128.*
1348. PrC **16,** 514/34; NL **89,** 208, 1912. *128.*
1348*a*. Sauer, A. JW **81,** 70/5, 1925. *124.*
1349. Schaper, Erich. Diss. Kiel, 1906. *99.*
1350. ———, W. Sitzber, Naturw. Ver. f. Schleswig-Holstein **10, 307,** 1896.
Veröfftl. d. Erdmagn. Station zu Lübeck 2. Teil. Schleswig 1909 (87 pp.) *100.*
Schardt
1351. Die geothermischen Verhältnisse des Simplon-Gebietes in der Zone des grossen Tunnels. Zürich 1914 (20 pp.). *273.*
1352. Intern. ZS f. Wasser-Versorgung **5,** No. 13/14, 1918. *274.*
1353. Schedler, A. WB 1922, 12. 10.; Na **11,** 459, 1923. *73.*
1354. Scheel, K.; Diesselhorst, H. WR **2,** 185/200, 1895. *20.*
Schelleng., J. C.; Nichols, H. W., s. (1163).
1355. Scheltle, H. BG **13,** 385/404, 1914. *219.*
1355*a*. Schering, H. GN 1908, 201/18. *121.*
———, K.
1356. GN 1884, 81/5; RE **20,** 430/4, 1884. *146.*
1357. GN 1884, 306/12; AP 3 **23,** 686/92, 1884. *81.*

1358. GN 1886, 185/95. *81.*
1359. PZ **12,** 1047/8, 1911. *82.*
1360. ———; Nippoldt, A. Erdmagnetische Landesaufnahme von Hessen. Darmstadt 1923. *69, 73.*
1361. Schewjakoff; Tanatar; Guschkoff; Kissjelnikoff. Go **98,** 529, 1923. *103.*
1362. Schiffner; Weidig; Friedrich. Radioaktive Wässer in Sachsen. Freiberg 1912. *131.*
1363. Schilowsky, Konst. DRP 322040 (16. 11. 13) †. *197.*
1364. Schindelhauer, F. JT **22,** 163/7, 1923. *202, 203.*
Schiótz, O. E.
1365. The Norwegian North Polar Expedition 1893/6; Bd. VIII. pp. 63 f. London 1900. *38.*
1366. VK 1907 No. 6 (28 pp.); VE **15,** 297, 1908. *38.*
1366*a*. Schlomka, Th. ZG **2,** 330/1, 1926. *150.*
Schlomka, T.; Wigand, A., s. (1622).
Schlumberger, Conr.
1367. DRP 269928 (6. 11. 12). *146, 160.*
1368. DRP 272603 (31. 5. 13). *158.*
1369. CR **170,** 519/21, 1920; Étude sur la prospection électrique du sous-sol. Paris 1920. *143, 146, 149, 158, 160, 165.*
1370. ———; Schlumberger, M. CR **174,** 471/80; Engg **113,** 870, 1922. *158.*
1371. Schlüter, W. Diss. Göttingen 1901; BG **5,** 401 ff., 1903. *215, 230.*
1372. Schmalz, Gust. DRP 404799 (21. 5. 24); Maschinenbau **3,** 639/41, 1924. *237.*
1373. Schmidle, W. JOG **2,** 6 9, 1912. *217, 265.*
Schmidt, Adolf
1374. SK **32,** 97/168, 1891. *273.*
1375. AM **19,** 1/66, 1899. *70.*
1376. Ergebnisse der magn. Beob. in Potsdam 1901, Berlin 1905. *72.*
1377. TM **11,** 181/3, 1906. *72.*
1378. VM **229,** Tätigkeitsber. 1910, 159/62. *99.*
1379. VM **217**; Abhdl. **3,** No. 4, 1/40, 1910. *73.*
1380. VM **225,** Berlin 1910. *81.*
1380*a*. TM **17,** 181/232, 1912; **18,** 1/6, 1913. *80.*
1381. VM **276,** Abh. **4,** No. 12, 1914. *73.*
1382. VM **272,** Tätigkeitsber. 1913, 107/16; 1914, 56/61. *78.*
1383. VM, Tätigkeitsber. 1914, 109/34, Berlin 1915, 87/106, 1916; VM **290.** *82.*
1384. VM **289,** Berlin 1916. *64.*
1385. MZ **33,** 481/92, 1916; Na **5,** 710/1, 1917; TM **25,** 123/38, 1920. *63.*
1386. Erdmagnetismus EM VI. **1,** 10, 266/396, Leipzig 1918. *81, 83.*
1387. PZ **22,** 152/9, 1921. *67.*
1388. VM **318,** Abh. **7,** No. 4, 1923; Na 1923, Heft 3; MZ **39,** 368, 1922. *99.*
1389. ZG **1,** 3/13, 1924. VM **332,** 1/21, 1926. *54, 68, 70, 153.*
1390. VM **322,** Bln. 1924. *54, 66.*
1390*a*. ZG **1,** 281/4, 1925. *151.*
1390*b*. ZG **2,** 38, 1926. *70.*

Schmidt, A.
1391. JW **53,** 28/55, 1897. *272.*
1391*a*. JW 1888. *241, 248.*
1392. BG **4,** 109/15, 1899; VS **1,** BG Erg. Bd. **1,** 254/8, 1902. *242.*
1393. BG **12,** 1/12, 1912. *220.*
1394. ———, Axel. JOG **10,** 59/62, 1921. *279.*
1395. ———, A. v.; Mack, K. Württbg. Jahrb. f. Statistik u. Landeskunde 1912, Heft I. Stuttgart. *215.*
———, C.
1396. Untersuchungen über die Standfestigkeit der Gesteine im Simplontunnel. Gutachten an die Direktion der Schweiz. Bundesbahnen, Bern 1907 (63 pp.). *35.*
1396*a*. PZ **27,** 715/6, 1926. *79.*
———, M.
1397. MB 1914, 71/98; 1915, 329/54; Veröfftl. d. bayer. Komm. d. Intern. Erdmessung Heft 2, No. 6, München 1919. *33.*
1398. MB 1922, 1/6. *32.*
Schmidt, W.
1398*a*. PZ **27,** 472/3, 1926. *121.*
1398*b*. PZ **27,** 371/8, 1926. *120.*
1398*c*. ZJ **46,** 431/3, 1926. *274.*
1398*d*. Schmitz. MM 1923, 29/41. *33.*
1399. Schmitt, Joh. Diss. Freiburg 1908. *129.*
1400. Schneider, R. MW **35,** 1909 (48 pp.) *226, 228, 230.*
1400*a*. Schneiderhöhn, H. Gl **62,** 197/205, 229/36, 1926. *36.*
Schober, Link. s. 862*a*.
1401. Schubert, J. MZ **12,** 185/7, 1895; **15,** 134/40; We **15,** 15/8, 43/6, 57/60, 1898. *272.*
Schuh, F.
1402. MML **32,** 1920 (18 pp.); Ka **15,** 231/5, 1921. *88, 100, 105.*
1403. MML **34,** 1923. MML **37,** 25/38, 1926. *105.*
1404. Schultze, R. Diss. Halle a. S. 1898. *146.*
1404*a*. Schulz, Karl. Fortschr. d. Min. **9,** 222/411, 1924. *268.*
Schumann, R.
1405. VG, NF. **14,** Berlin 1904. *33.*
1406. WA 1920, 15/20. *58.*
1406*a*. Bergbau und Hütte 1920, 1/4; Mitt. d. Inst. f. Kohlenvergasung. Wien **2,** 49 ff., 1920.
1407. ÖB **1,** 1920; **2,** 156/8, 1921; **3,** 198/9, 1922; MM 1920. *58.*
1408. ZJ **41,** 352/5, 1921. *15, 58.*
1409. Pe **19,** 648/56, 1923. *48, 58.*
1409*a*. ZJ **46,** 25/9, 1926. *48.*
1409*b*. BG **15,** 215/8, 1926. *27.*
1409*c*. ———; Grengg. ÖB 1920, Heft 5 and 6; Pe **19,** 19. 7. 23. *58.*
1409*d*. ———; Petraschek, W. BHJ **69/70,** Heft 4. *58.*
1410. Schünemann, J. Diss. Göttingen 1910 (35 pp.). *129.*
Schuster, A.
1411. PT **180** 1, 467/518, 1889; **208** 1, 163/204, 1908. *66.*
1412. VS **3,** 22, 1909. *228.*

1413. TM **19,** 19/22, 1914. *79, 80.*
1413*a*. NL **97,** 455, 1916. *16.*
Schwarz, Gottw.; Falta, W., s. (442).
Schweidler, E. v.
1414. PZ **10,** 847/9, 1909. *130.*
1414*a*. WB **127,** 515 f., 1918; AP 4, **63,** 726/38, 1920. *120, 152.*
1414*b*. EM VI, **1,** 235/65. *107.*
1415. ———; Kohlrausch, Fr. Atmosphärische Elektrizität; in Graetz, Handbuch d. Elektrizität u. d. Magnetismus. Bd. III. Lfg. 2. Leipzig 1915. *120, 121.*
———; Mache, H., s. (1018).
———; Meyer, Ste., s. (1100).
———; Mache, H.; Meyer, Ste., s. (1017).
1416. Schweizer, G. BNM **35,** 2, 411/513; **35** 3, 114/74, 1862; **37,** 96/171, 1864. *46, 59, 100.*
Schweydar, W.
1417. BG **9,** 41/77, 1907. *30, 36.*
1418. VG **54,** Berlin 1912 (58 pp.); BB 1914, 454/65; VG **66,** Berlin 1916 (51 pp.); VG **79,** Berlin 1919 (10 pp.). *30, 36.*
1419. AN **203,** 101/16, 1916. *36.*
1420. VZE **38,** Berlin. *30, 36.*
1420*a*. Na **5,** 593/600, 1917. *36.*
1421. ZpG **26,** 157/62, 1918. *20, 51, 56, 88.*
1422. ZJ **41,** 175/83, 1921; **42,** 179/82, 1922; **43,** 307/11, 1923. *20, 24, 26.*
1423. Jahresber. d. Station Potsdam 1922, Deutsche Seismol. Ges., Tätigkeitsber. d. Erdbebenarten. *226.*
1424. JH **4,** 2. Lfg., 352/68, 1924. *20, 56, 57.*
1425. ZG **1,** 81/9, 1925. *48.*
1425*a*. ZG **2,** 145/50, 150/3, 1926. *25, 38.*
1425*b*. Schweydar, W.; Reich, H. BG **17,** 121/47, 1927; ZG **2,** 350/1, 1926. *215, 237, 238, 248, 249, 251, 259, 260, 261.*
Schwinner, Rob.
1426. ZG **1,** 166/7, 1925. *42.*
1426*a*. ZG **2,** 126/34, 214/6, 1926. *39.*
———; Heritsch, F., s. (713).
1427. Seeliger, R. AP 4 **62,** 446 ff., 1920. *152.*
1428. Seismos-Gesellschaft. Erforschung von Gebirgsschichten usw., Hannover 1922. *250, 261.*
1429. Sekija, S. TrSJ **11,** 175/7, 1887. *246.*
Sella, A.; Oddone, E., s. (1193).
1430. Sénarmont, H. de. CR **25,** 459/61, 707/10; ACh **21,** 457/76; ACh **22,** 179/211; BU **6,** 226/8, 1847; AP 2 **73,** 191/3; **74,** 190/202; **75,** 50/62, 1848. *270.*
1430*a*. Sénouque, A. CR **144,** 535/8, 1907. *72.*
1431. Serpieri, S. C. A. Rend. Inst. Lombardo **13,** 193/4, 1880. *155.*
1431*a*. Service, Jerry, H. Sc **63,** 616/7, 1926. *223.*
1432. Sharp, W. H. Electrical Review **55,** 285/7, 357/8, London 1904. *152.*
1433. Shaw, E. W. Sc **46,** 553/6, 1917. *56.*

1434. ———, H.; Jones, Lancaster E. PrP **35,** 151/66; 204/12; NL **111,** 849/51, 1923; MgM **32,** 18/25, 86/92, 1925. *20.*
1435. ———, J. J. CR I. Conf. Union géod. géoph. intern. sismol. Rome 2. bis 10. 5. 1922, S. 52/53. *229.*
1436. ———, P. E. PT **216,** 349/92, 1916. *9.*
1437. ———; Davy, N. PrS **102,** 46/7, 1922. *9.*
1438. Shaxby, J. H. JSJ **1,** 234/7, 1924. *86.*
Shida, Toshi
1439. Science and engineering, Kyôto, Imp. Univers. **4,** 1912. *36, 154.*
1439*a*. TrSJ **9** 1, 32/46, 1886. *154.*
Sieberg, A.
1440. BG **13,** kl. Mitt. 114/20, 1914; NW **21,** 443/6, 1922; Mitt. d. Hauptstation f. Erdbebenforschung in Jena. *219.*
1442. VJ **1,** 96 S., 1922. *217, 219.*
1443. Geologische, physikalische und angewandte Erdbebenkunde, Jena 1923 (572 pp.). *31, 204, 207, 208, 211, 212, 215, 216, 217, 218, 219, 220, 224, 228, 230, 233, 234, 239, 240.*
1443*a*. ZG **2,** 39/42, 1926. *219.*
———; Lais, A., s. (893).
1444. Siemens, C. W. DP **221,** 48/54; PrS **24,** 317/21, 1876. *14.*
1445. Siemens & Halske, A.-G. DRP 413764 (23. 3. 23). *240.*
1446. Sieveking, H. PZ **6,** 700/3, 1905. *117.*
1447. ———; Lautenschläger, L. PZ **13,** 1043/51, 1912. *131.*
———; Engler, C.; Koenig, A., s. (395).
Silva, G.; Lorenzoni, G., s. (979).
1447*a*. Simcock. Fuel **5,** 157/63, 1926. *265.*
1447*b*. Simoens, G. VS **2,** 267/8, Haag 1907. *219.*
Simpson, C. George
1448. PM **19,** 715/25; NL **83,** 147, 1910. *150.*
1449. NL **90,** 411/2, 1912. *150.*
1450. ———; Wright, C. S. PrS **85,** 175/99, 1911. *129.*
1451. Singer. Die Bodentemperatur auf der kgl. Sternwarte bei München und der Zusammenhang ihrer Schwankungen mit den Witterungsverhältnissen. München 1890. *272.*
1452. Skey, W. New Zealand Inst. Trans. a. Proc. **3,** 232/6, 1871. *146.*
Sludski
1453. Nachr. d. k. russ. geogr. Gesellsch. **29,** 269/73, 1893; Mém. Soc. Geogr. Génève **33,** 85/6, 1894. *46, 100.*
1454. Nachr. d. k. russ. geogr. Gesellsch. **32,** 510/24, 1896. *46.*
1455. Smeeth, W. F.; Watson, H. E. PM 6 **35,** 206/14, 1918. *125.*
1456. Smith, F. E. PT **223.** 175/200, 1922. *80.*
———, O. F.; Wright, J. R., s. (1648).
1457. Smith, T. Townsend. PR 2 **8,** 721/37, 1916. *90, 95.*
1457*a*. Smith-Rose, R. L. NL **116,** 426/7, 1925. *201.*
1458. Smock. TrM **4,** 1875; Van Nostrand's Engin. Mag. **16,** 262/7, 1877. *103.*
1459. Smyth, H. L. MG **36,** II., 2, 336/73, Wash. 1899. *77, 84, 102, 103, 104, 105.*
1460. ———, L. B. PM 6 **24,** 632/7, 1912. *129.*
———; Joly, J., s. (787).

1461. Socolow, A. P. Jph 6 **5,** 153/63, 1924. *133.*
Soddy. *108.*
1462. Soess, F. E. GR **11,** 144/68, 249/63, 361/400, 1920. *32.*
1463. Sollàs, W. J. GM 4 **8,** 502/4, 1901. *283.*
1464. Sommer, E. Ueber die Radioaktivitätsverhältnisse der natürlichen Heilquellen des deutschen Sprachgebietes. München 1910. *131.*
1465. Sommerfeld, A. CRB **1,** 659/71, 1911; JT **4,** 157 ff., 1911. *200.*
1465*a*. Somville, O. Publ. Bur. Centr. Séism. Int. (A) **2,** 65/76, Paris 1925. *224.*
1465*b*. Sonder, Richard A. VZ **67,** 177/97, 1922. *133.*
1466. Spencer, J. W. AJ **35,** 561/74, 1913. *36.*
1467. Stadler, G. Diss. Zürich 1889; VZ **34,** 12/46, 1889. *268.*
1468. Stäger, A. ZG **1,** 209/13, 1924/5. *150.*
1469. Stainier, X. ABelg **24,** 979/92, 1923. *283.*
Stapff, Fr. M.
1470. Studien über die Wärmeverteilung im Gotthard, I. Bern 1877; Trans. Nord England Inst. of Mining a. Mechan. Engineers **33,** 19/34, Newcastle-upon-Tyne 1884. *273, 274.*
1471. Arch. Anat. Physiol. 1879 (Suppl. Bd.) 72/145; Cuyper, Revue Univ. **5,** 534/59; **6,** 1/23, 464/81, 1879; **7,** 1/48, 1880. *274.*
1472. MZ **16,** 410/4, 518/20, Wien 1881. *279.*
1473. Les eaux du tunnel de St. Gothard, Altenburg 1891. *274.*
1474. Steeb, Christian v. JGW **60,** 751/78, 1910; MZ **30,** 203/4, 1913. *274, 279.*
———; Gorjanović-Kramberger; Melkus, s. (572).
Steiner, L.
1475. Res. d. wiss. Erf. d. Balatonsees I, **1,** Geophys. Anh. III, S. 1/**30.** *101.*
1476. TM **13,** 57/62, 1908. *152, 154.*
1477. Die magnetischen Erscheinungen der Erde (ungar.), Budapest 1923 (207 pp.), (Ref. ZaG **1,** 317, 1925). *69.*
1478. Stelling, Ed. BAP 1913, 299/302. *97.*
1478*a*. Stenquist, D. Mém. Direction Générale des Télegr. d. Suède 1924 (14 pp.), 1925 (79 pp.). *154.*
1479. Stephan, H. v. BB 1886 2, 787/95; NR **1,** 425/7, 1886. *148.*
1480. ———, Irene. Str **16,** 560/74, 1924. *131.*
1481. Stephenson, E. B. PR 2 **15,** 519, 1920. *240.*
Sterneck, R. v.
1482. Mitt. d. k. u. k. milit.-geogr. Inst. Wien **7,** 1887; **8,** 1888; **9,** 1889; ZJ 1888, 157. *29.*
1483. Relative Schwerebestimmungen durch Pendelbeobachtung., ausgeführt durch die k. u. k. Kriegsmarine in den Jahren 1892 und 1894, Wien 1895. *15.*
1484. Resultate d. wiss. Erf. d. Balatonsees I, **1,** Geophys. Anh., S. 1/30, 1908. *42.*
1485. WA 1910, 12/4, *42.*
1486. Stöckl, K. AM **29,** 7 (42 pp.), 1922. *99.*
1487. Stoklasa, Jules; Penkava, Jos.; CR **179,** 819/22, 1924. *128.*
1488. Stonely, R. PrS **106,** 416, 1924. MNGS **1,** 280/2, 1925; *206.*

1489. Stoye, Karl. JT **19,** 58/72, **20,** 303/5, 1922. *201, 202.*
1490. Strahan, A.; Cox, H. NL **101,** 257/8, 1918. *98.*
1491. Streichen, A. PM 6 **31,** 401/3, 1916. *131.*
1492. Streintz, Fr. WB **111,** 345/78; AP 4 **9,** 854/85, 1902; PZ **4,** 106/8, 1903; JR **10,** 221/51, 1913. *140.*
1493. Stremme, H. ZM 1908, 271/6, *282.*
1494. Strombeck, v. Karsten's Archiv f. Bergbau **6,** 431/8, Berlin 1833. *156.*
1495. Strutt, J. R. Ra **3,** 161/7; PrS **77,** 472/85; **78,** 150/3, 1906. *133, 281.*
1496. Stutzer, F.; Gross, W.; Bornemann, K. ME **15,** 1/11, 1918. *90, 94.*
1497. Suess, F. E. VGW 1900, No. 2, 55/63. *31.*
1498. Summers, R. E. J. Engg. new-record New York **91,** 1044/7, 1923. *265.*
Sundberg, Karl
1499. TT **52,** 95/6, 1922. *180, 186.*
1500. CJ **46,** 819/20, 1925. *180, 189, 357.*
1500*a*. BHJ **73,** 195/8, 1925. *179, 189.*
1500*b*. ME **23,** 288/98, 1926; Analele Minelor **10,** 1927. *189.*
1500*c*. BHJ **74,** Heft 4, 1926. *161, 176, 187, 189, 191.*
1500*d*. Sundberg, K., Lundberg, H., Ecklund, G. Sveriges Geolog. Unders. Aarsb. **327,** C 17. 1925; MgM **31,** 346/9, 1925. CJ **47**, 1926. *189, 190.*
1501. Sundholm, H. TT 1896. *106.*
1502. Supan, A. G. PG **41,** 294, 1895. *274.*
1503. Süring, R. MZ **35,** 94/5, 1918. *130.*
Swann, W. F. G.
1504. JFr **195,** 433/74, 1923. **201,** 143/76, 1926. *150, 152.*
1504*a*. Sc. **21,** 90/5, 1925. *70.*
1504*b*. Swick, C. H. BRC **11,** 56/8, 1926. *16.*
1505. Szabó, Jos. Mathém. és Természettee dományi Ertesitö **4,** 138/40, Budapest 1886. *279.*
Szirtes, S.; Rudolph, E., s. (1320), (1321), (1322).

Tabesse, E.
1505*a*. CR 180, 382/4, 1925. *101.*
1505*b*. CR **182,** 234/6, 1926. *101.*
Tait; Thomson, W.; Helmholtz; Wertheim s. (1534).
Tams, E.
1505*c*. Geogr. Zs. **22,** 315, 1916. *217.*
1506. GR **10,** 1/14, 1919. *20.*
1507. ZM 1920, 182 9. *32.*
1508. Mitt. d. geogr. Ges. z. Hamburg **33,** 37/67, 1921; ZM 1922, 385/7. *219.*
1509. ZM 1921, 44/52, 75/83. *222.*
1510. PG **68,** 245/6, 1922. *216.*
1511. Na **11,** 49/60, 1923. *212.*
1512. ZG **1,** 68/9, 1924/5. *103.*
1513. ZG **1,** 187/91, 1924/5. *216, 220.*

———; Prey, A.; Mainka, C., s. (1258).
1514. Tamura, S. Tetsu. MWR **33,** 296/302, 1905. *272.*
Tanakadate, Aikitsu
1515. Tokyo Univ. Mém. **5,** App. 1885 (31 pp.); PrE **12,** 544/60, 1883/4. *80, 88.*
1516. BG, Erg. Bd. **2,** 307/8, 1904. *276.*
1517. ———; Nagaoka, H. Journ. Coll. Sci. Univ. Japan. Vol. V, pt. **2,** 149/96, Tokyo 1892. *97.*
Tanatar; Schewjakoff; Guschkoff; Kissjelnikoff, s. (1361).
1518. Tarr, R. S.; Martin, L. BGA **17,** 29/64, 1906. *106.*
1519. ———, W. A. EG **7,** 647/61, 1908. *31.*
1520. Tedone, O. Allgemeine Theoreme der mathematischen Elastizitätslehre. EM IV, 4, 55/124. 1906. *207.*
Thalén, T. Rob.
1521. SAH **20,** No. 3, Stockholm 1883. (66 pp.). *103, 105.*
1522. ÖfvS **31,** No. 2, 5/19, 1874. *103, 105.*
1523. ÖfvS **31,** No. 8, 3/23, 1874; Nova Acta Reg. Soc. Sci. Upsala. 1877 (Vol. extraordin.) No. 16; JA **34,** 17/124, 1879; **54,** 358/80, 1899. *103, 105.*
1524. BH **34,** 160/1, 1875; JA 1866, 152 ff. *105.*
1525. The electrical ore finding Company. DRP 152519 †. *167.*
1525*a*. Thiene, H. Temperatur und Zustand des Erdinneren, Jena 1907. *267.*
1526. Thiesen. Trav. et Mém. d. Bur. intern. des poids et mesures. **7,** Paris 1890. *20.*
1527. Thom. EG **20,** 524/30, 1925. *274.*
1528. Thoma, E. Diss. Freiburg 1905, Karlsruhe 1906. *274.*
———; Koenigsberger, J.; Leier, F., s. (844).
1529. Thomson, A. B. Oil Fields of Russia, 2. Aufl., London 1908. *282.*
———, W.
1530. De motu caloris per terrae corpus. Glasgow 1846. *267.*
1531. BR 1847 2, 38/9. *154.*
1532. PM 4 **22,** 23/34, 121/35, 1861. TrEd **22** 2, 405/27, 1861. *272.*
1533. TrEd **23,** 157/70, 1864. *267.*
1534. ———; Tait; Helmholtz; Wertheim. Handbuch der theoretischen Physik I, **2.** Brunswick 1874. *267.*
1534*a*. Thomson. TM **31,** 113/20, 1926. *129.*
1535. Thornton, W. M. PM 6 **38,** 705/7, 1919. *268.*
1536. Thorpe, T. E.; Rücker, A. W. PrS **36,** 5/10, 1883/4. *100*—s. a. (1313).
1537. Threbfall, R.; Pollock, J. A. PT **193,** 215/58, 1899. *21.*
1538. Tiberg, E. Wermländska Bergsmannaföreningens Annales 1883; BH **43,** 388/9, 1884. *84, 102, 103.*
Tigerstedt, A. F.
1539. Fe **5,** No. 5 (6 pp.). Helsingfors 1892. *100.*
1540. Fe **14,** No. 8, 1897/9. *100.*
Tillo, Al. v.
1541. CR **112,** 680, 1891. *100.*
1542. NL **44,** 83, 1891. *100.*
Timpe, A.; Müller, C. H, s. (1144).

1543. Tittmann, O. H.; Hayford, John, F. VE **15** 1, 198/236, and Dutton, Cl., PrW **8,** 25/40; 1906. *38, 41.*
1543*a*. Toepler, A. BB 1883, 125 ff., *83.*
1544. Toll, v. Verhandl. d. Deutsch. Geogr. Tages 1891, 53/64. *273.*
1545. Traubenberg, H. Rausch, v. PZ **4,** 460/1, 1903. *130.*
———; Abraham, M.; Pusch, J., s. (5).
Trebra, v.
1546. ATr **3,** 59/64, 1818. *266.*
1547. JGW **8,** 656, 806, 1857. *96.*
1548. Treleaven, C. L.; Mc Lennan. PM 6 **30,** 415/27, 1915. *122.*
1549. Trowbridge, C. C. PR **24,** 527/9, 1907. *153.*
1550. True, H. Diss. Göttingen JT **5,** 125/75, 1911. *200.*
1551. Trüstedt, O. ZpG **20,** 159/62, 1912. *196.*
1551*a*. Tscherepenikoff, J. BJP **1,** 277/8, 1925. *126.*
1552. Tumlirz, O.; Luggin, H. WA **23,** 93/4, 1886. *95.*
1553. Turley, B. BH **23,** 1/3, 1864. *104.*
1553*a*. Tuve, M. A.; Huff, C. TM **32,** 17/25, 1927. *121.*
Tuwim, L.; Myssowsky, L. s. 1150*a*.

1554. Ubach, José. Bol. mens. Obs. del Ebro **1,** No. 1, 51/5, 82/4, Barcelona 1910. *148.*
Uhlich, P.
1555. JS 1899. *84, 103.*
1555*a*. Cf. (326). *105.*
1555*b*. Uljanin, W. Journ. Russ. Phys. Chem. Ges. Phys. Tl. **56,** 75/6, 1924. *80.*
1556. Uller, K. AP 4 **56,** 463/96, 1918; ZP **6,** 298/302, 1921; VDP 3 **3,** 8/13. 1922. *206.*
Umani, Ant.; Brucchietti, G., s. (253).

Venske, Osw.
1557. GN 1909, 219/29. VM **327,** 91/6, 1925. *84, 85.*
1558. VM **284,** 61/9, Berlin 1915. *83.*
1559. VM Tätigkeitsber, f. d. J. 1915, 60/7, Berlin 1916. *81.*
1560. VM Tätigkeitsber, f. d. J. 1917/9, Anhg. S. 80/9. *81.*
1561. VM **320,** Tätigkeitsber, f. d. J. 1920/3. Berlin 1924. *76.*
1562. Venturi, A. Teoria della bilancia di torsione di Eötvös. Estratto dagli Atti della R. Acad. di Scienze; Lettre ed Arti, Serie 3a. Vol. IX. Palermo 1908; VE **16,** 334, 1909. *20.*
Vicentini. *234, 236, 237.*
1563. Viereck, Paul. Diss. Halle 1910. *126.*
1564. Villarceau, Yvon. CR **89,** 113/9, 1879. *14.*
1564*a*. Vingershoets, F. I. G. ZBB **34,** 538, 1926. *126.*
1565. Viol, F. Diss. Halle 1916 (45 pp.). *126.*
Visser, S. W.
1566. MMB 1921, No. 7. *211.*
1567. MMB No. 16, 1925 (24 pp.). *206.*
Vohsen, Fr.; Hammer, W., s. (636).

Voigt, W.
1568. GN 1896, 236/51; 1897, 184/8; AP 3 **60,** 350/67, 1897; **64,** 95/100, 1898. *270.*
1569. Lehrbuch der Krystallphysik. Leipzig-Berlin 1910. (964 pp.). *90, 95, 140, 271.*
1570. ———; Kinoshita, S. GN 1907, 123/44. *92, 95.*

1571. Wagner, A. ZaG **1,** 225/46, 1924. *104.*
1572. ———, C. J. VGW **34,** 743/50, 1884. *273.*
1573. ———, Em. Engg **116,** 583/9, 1923. *20.*
Walferdin, H.
1574. CR **2,** 505, 1836; BGF **7,** 193/6, 261/2, 1835/6; CR **36,** 250/4, 1853; **44,** 971/5, 1857. *275.*
1575. CR **4,** 977, 1837; **6,** 503/6, 1838; BGF **9,** 254/8, 1837/8; **11,** 29/30, 1839/40; ACh **69,** 35/40, 1838. *266.*
1576. Walker, C. V. PT **152,** 203/19, 1862. *155.*
1577. Wanach, B. VZE No. **34** (25 pp.), Berlin 1919. *36*
1578. Waring, G. A. U. S. Geolog. Survey, Water-Supply, Pap. 338 (410 pp.), 1915. *279.*
Warner, E. P.; Norton, F. H., s. (1188).
1579. Washington, H. S. BGA **33,** 375 ff., 1922. *38.*
1580. ———; Larsen, E. S. JWA **3,** 449/52, 1913. *96.*
1581. Watanabe, Nob.; Kawamura, Toshio. JJA **1,** 191/1924. *86.*
1581*a*. Waterman, A. F. PR 2 **21,** 540/9, 1923. *141.*
1582. Waters, J. W. PM 6 **18,** 677/9, 1909; 6 **19,** 903/4, 1910. *124.*
1583. Watson, H. E.; Pal, G. PM 6 **28,** 44/51, 1914. *128.*
———; Smeeth, W. F., s. (1455).
1584. ———, W. PM 6 **7,** 393/9, 1904. *83.*
1585. Watt, R. A. Watson. PM 6 **45,** 1010/26, 1923; PrS **102,** 460/78, 1922; PrP **37,** D. 23/31, 1925. *202.*
1586. ———; Appleton, E. V. PrS **103,** 84/102, 1923. *202.*
———; ———; Herd, J. F., s. (55).
1587. Weber, Leonh. BB 1885, 1105/13 (Ref. MZ **3,** 547/9, 1886). *85.*
1588. ———, Max. ZM 1923, 388/92. *125.*
1589. ———, Rob. H. VZ **23,** 209/41, 1878; Neuchâtel, Soc. Sci. Bull. **12,** 394/418, 687/95, 1880. *268, 271.*
———, Wilhelm E.
1590. Result. a. d. Beob. d. magn. Vereins i. J. 1837, p. 81; AGA **5,** 1853 (58 pp.); W. Weber's Werke **2,** Abh. 5, 26/27. *84.*
1591. Result. a. d. Beob. d. magn. Vereins i. J. 1841, 64/9. *99, 269.*
———; Gauss, C. Fr., s. (520).
1592. Wegener, Alfr. Die Entstehung der Kontinente und Ozeane (Die Wissenschaft **66,** Braunschweig 1922) (135 pp.). (Span. trans. by Inglada, V., Revista de Occidente 1924, p. 171.) *32, 39.*
1593. ———, K. GN 1912, 267/384. *211, 223.*
Weidig; Schiffner; Friedrich, s. (1362).
Weigelt, O.
1593*a*. Gl **62,** 878, 1926. *261.*
1593*b*. ZaC **39,** 999/1004, 1926. *357.*

1594. Weinberg, B. P. Tomsk. Sib. Bull. Tomsk. Inst. Techn. **43,** 9/10, 1923. *103.*
1595. Weinstein, B. ETZ **5,** 201/4, 256/8, 289/92, 353/61, 1884; **6,** 273/7, 335/7, 366/8, 1885; **7,** 370/8, 1886; Die Erdströme im deutschen Reichstelegraphengebiet und ihr Zusammenhang mit den erdmagnetischen Erscheinungen, Braunschweig 1900. *148, 152.*
1596. Weiss, P. EEl **7,** 487/508; **8,** 56/68, 105/110, 1896; Jph 3 **5,** 435, 1896. *90.*
1597. Wellmann, H. Diss. Hamburg 1923. *224.*
1598. Wells, R. C. U. S. Geolog. Survey Bull. 548, Wash. 1914 (73 pp.). *146, 157.*
1598*a*. Welo, L. A. Sc 2 **64,** 453/5, 1926. *95.*
1599. Wenner, Fr. SS **258,** 469/78, Washington 1917. *141, 145, 165.*
1600. Wentworth, H. A. TrM Bull. **66,** 642, 1912. *157.*
1601. Werkstätten f. Präzisionsmechanik und Optik C. Bamberg. DRP 343620 (14. 1. 21). *24.*
1601*a*. Werner, H. Gl. **63,** 633/7, 1927. *282.*
Wertheim; Thomson, W.; Tait; Helmholtz, s. (1534).
1602. Werveke, L. van. EH **16,** 176/9, 1920/2. *283.*
1603. Weszelsky, Jul. v. CRB **1,** 684/93, 1911. *117.*
1603*a*. Weyl, Alf. Rich. Zs. f. Flugtechnik **16,** 451/8, 470/4, 1925. *239.*
1604. White, Dav. JWA **7,** 312, 1917. Presid. Address Geolog. Soc. Americ. Dec. 27, 1923. *46.*
1605. ———, J. C. West Virg. Geolog. Surv. County Rep. 1918. *282.*
Whitehead, T. T.; Chapman, S., s. (295), (296).
Whittemore, L. E.; Dellinger, J. H. and Kruse, S., s. (345).
Wiechert, Emil
1606. GN 1899, 195/208. *204.*
1607. VS **1;** BG Erg.-Bd. **1,** 264/80; PZ **2,** 593/6, 605/9, 1901; AGA, NF. **2,** No. 1, Berlin 1903. *230, 232, 233, 234, 236.*
1608. PZ **4,** 821/9, 1903; BG **6,** 435/50, 1904. *233, 234.*
1609. VS **2,** BG, Erg.-Bd. **2,** 41 f., 1904. *227.*
1610. VS **3,** Anh. 25, Rom 1906. *282.*
1611. GN 1906, 376/80. *233, 236.*
1612. (and Zoeppritz), GN 1907, 415/549. *204, 206, 211, 214, 225, 247.*
1613. ZJ **29,** 381/2, 1909; Ra **7,** 122, 1910. *117.*
1614. GN 1923, 57/70. *259.*
1615. BSG 1, 7/8, 1923. *214, 233, 248, 268.*
1615*a*. GR **17,** 339/48, 1926. *260.*
1616. ———; Geiger, L. PZ **11,** 294/311, 1910. *213.*
1617. Wiedemann, G. AP 2 **126,** 1/38; PM **30,** 366/70, 1865. *92.*
1618. Wiedenhoff, S. JT **18,** 242/60, 1921. *202.*
Wigand, Alb.
1619. PZ **22,** 623/5, 1921. *150.*
1620. PZ **25,** 445/63, 1924. *122.*
1621. PZ **25,** 684/5, 1924; TM **30,** 33/4, 1925; Luftelektrische Untersuchungen bei Flugzeugaufstiegen, Berlin 1925 (52 pp.). *123.*
———; Everling, E., s. (440).
1622. ———; Schlomka, T. AP 4 **75,** 279/325, 1924. *123.*

Wild, H.
1623. MP 7 **31,** No. 12, 1883 (24 pp.); BAP **29,** 296/301, 1884; RE **20,** 167/94, 1884. *126, 148.*
1624. RM **8,** No. 7, 1883 (81 pp.). *79.*
1625. MP 7 **36,** No. 1. *76.*
1626. Wilfer. MZ **39,** 360/1, 1922. *130.*
1627. Wilip, J. Acta et Commentationes Universitatis Dorpatensis (A) **6,** No. 10 (12 pp.) 1924. *214.*
1628. Willert, H. Bu **11,** 1918. *282.*
1629. Williams, S. R. PR 2 **22,** 204/5, 1923. *81, 167.*
Williamson, Ersk. D.; Adams, Leason, H., s. (9).
1630. Willmann, E. v. EH **10,** 801/3, 1908. *274, 279.*
1631. Wilser, B. BHJ **71,** 22/30, 1923; **72,** 40/8, 1925. *179.*
1632. Wilser, J. L. JM 1924, 486/99. *32.*
1632*a*. Wilski, P. AV **35,** 369/79, 1923. *104.*
1633. Wilson, C. T. R. PrS **68,** 151/61, 1901; **69,** 277/82, 1902; **80,** 537/47, 1908. *122, 151.*
1634. ———, Ern. El **83,** 197/8; NL **102,** 478, 1919. *91.*
1635. ———; Herroun, E. F. NL **103,** 399, 1919; PrS **105,** 334/5, 1924. *90, 141.*
Wilson; Briggs; Owen, s. (245 a).
1636. ———, H. A. PR 2 **20,** 75/7, 1922. *9.*
1637. Wind, C. H. Diss. Groningen, 1894. *79.*
1638. Winnacker. ZBB **32,** 57/8, 1924. *123.*
1638*a*. Wintermeyer. Bb **38,** 437/9, 458/62, 1925. *357.*
1639. Wipple, Rob. S. JO **10,** 455/73, 1925. *97.*
1639*a*. Witte, H. ZG **2,** 181/7, 1926. *126, 129.*
Witte, H.; Ludewig, P., s. (1000).
1640. Witting, Rolf. Fe **39,** No. 5 (347 pp.) Helsingfors 1908. *33.*
Woeikoff, A. von
1641. MZ **7,** 381/5, 1890. *273.*
1642. ZM **21,** 50/62, 399/408, 1904. *272, 273.*
1642*a*. Wolf, F. JT **19,** 289/99, 1922. *202.*
Wolff, F. v.
1642*b*. ZDG **60,** 431/65, 1908. *281.*
1642*c*. Der Vulkanismus. 1. Band. Stuttgart 1914 (711 pp.) *278.*
———, Hans G.
1643. VM 277 Abh. **5,** No. 1 (24 pp.) Berlin 1914. *99.*
1643*a*. Diss. Berlin 1913 (117 pp.); BG **14,** 206/14, 1916. *16, 39.*
1644. ZpG **31,** 113/8, 1923. *33.*
1645. Wologdine. CR **148,** 776/7, 1909. *95.*
Wood, H. O.; Anderson, J. A., s. (37).
1646. Wright, C. S. PM 6 **17,** 295/318, 1909. *122.*
———; Mc Lennan, J. C., s. (1021).
———; Simpson, G. C., s. (1450).
1647.———, F. E. JG **32,** 462/4, 1924, *279.*
1648. ———, J. R.; Smith, O. F. PR 2 **5,** 459/82, 1915. *119, 120.*
1648*a*. Wrinch, D.; Jeffreys, H. MNGS **1,** 15/22, 1923. *258.*

Wulf, Theod.
1649. PZ **8,** 246/8, 527/30, 780/1, 1907; **10,** 152/7, 251/3, 1909; **26,** 352/3, 1925. *117, 122.*
1650. Ra **5,** 170/2, 1908; PZ **11,** 1090/5, 1910. *117.*
1651. PZ **15,** 250/4, 1914; **24,** 299/300, 1923; **25,** 109/11, 1924. *117.*
———; Gockel, A., s. (566).
1651*a*. Wünsch. ZVJ 1923, 189/90. *20.*
1652. Wurm; Zimmerhackel. Jahresber. d. Oberrealschule in Böhmisch-Leipa 1881/2. *96.*
1652*a*. Würschmidt, J. Theorien d. Magnetismus (Sammlung d. Wissenschaft 74); Theorien d. Entmagnetisierungsfaktors usw. (Samml. d. Wiss. 78), Braunschweig 1925. *88.*

1653. Yamagawa, Kenjiro. Journal of the College of Sci. Imp. Univ. Japan **2,** 263/81, 1888. *268.*

1654. Zachariae. VE **15** 1, 307/10, 1906. *42.*
1655. Zaddach, E. G. VR **8,** 195/306, 1851. *96.*
1656. Zeeman, P. Verslag van de gew. Vergad. WA **26** 1, 451/62, 1918. *9.*
1657. Zeil. CR **170,** 597/600, 1920. *38.*
1658. Zeisberg, Max. Diss. Breslau 1899. *99.*
Zeissig, C.
1659. Notizbl. d. Ver. f. Erdkde. i. d. Grossh. geolog. Landesanstalt z. Darmstadt. 4. Folge, Heft 33, 1912. *211, 218.*
1660. BG **11,** 520/8, 1912. *218.*
1661. Vortrag Naturforschervers. Leipzig 1922. *239, 258.*
1662. Zenneck, J. AP 4 **23,** 846/66, 1907. *200.*
1663. ———; Rukop, H. Lehrbuch der drahtlosen Telegraphie. 5. Aufl. Stuttgart 1925. *193.*
Zimmerhackel; Wurm, s. (1652).
1664. Zirkel, F. Lehrbuch der Petrographie. Bd. I. 428/37, Bonn 1866. *96.*
1665. Zoellner. LB **21,** 281/4, 1869; **23,** 479/575, 1871; **24,** 183/92, 1872; Aph **150,** 131/150, 1873; PM **43,** 345/65, 446/69, 481/502, 1872. *234.*
1666. Zoeppritz. Wagners Geograph. Jahrbuch **8,** 26/30, 1880. *279.*
1667. —, K. GN. 1916, 66/84. *206, 214.*
1667*a*. ——; Geiger, L. GN 1909, 400/28. *212.*
1668. ———; ———; Gutenberg, B. GN 1912, 121/206. *211, 224.*
———; Wiechert, E., s. (1612).
1668*a*. Zotz. ZpG **34,** 72/5, 1926. *357.*
1669. Zschaage, W. ETZ **46,** 1215/9, 1948, 1925. *161, 172.*
1670. Zsigmondy, Arp. ÖB **51,** No. 22. (Ref. MM **6,** 107/8, 1904.) *103.*
1670*a*. ———, Wilhelm. JGW **28,** 659 ff., 1878. *279.*
1671. Zuber, Stan. ZBB **33,** 123/7, 1925. *282.*
1672. Zuschlag. Engg. **123,** 327/9, 1927. *137, 145, 175, 182.*

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